Errata to IRTS HAREC Amateur Radio Station Licence Study Guide

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Visit irts.ie/errata for the most recent clarifications.

Page 193 · Section 13.3.4
IF Filter, Table 13-A

Row *FM 12.5 kHz*
should read *FM 7.5 – 16 kHz*

Page 229 · Section 15.7
Half-Wave Antenna, second line

It is designed to be used on a specific, narrow range of frequencies, for example, on the 20 m band. However, it can be also operated on the harmonics of that frequency, for example, on 10 m.

should read: *It is designed to be used on a specific, narrow range of frequencies, for example, on the 40 m band. It can be also operated on the harmonics of that fundamental frequency. If centre-fed, its feed point impedance is easier to match on the odd (3rd, 5th, …) harmonics, for example, on 15 m, than on the even ones (2nd, 4th, …) like 20 m.*

Page 234 · Section 15.9
Non-Resonant Wire Antennas
third line

Its impedance is only resistive with no reactance.

should read: *Its impedance is only resistive, with no reactance, if fed in the centre, or anywhere else except close to its ends.*

Page 234 · Footnote 287

The feed point impedance will be close the fundamental.

should read: *The feed point impedance, at the centre, and anywhere else except close to its ends, will be higher, however, its reactance will remain low and easy to match.*

Page 235 · Footnote 290

It is harder on frequencies that are even harmonics (2nd, 4th…) of the fundamental. The antenna is once again resonant, i.e., it has no reactance, however, its purely resistive impedance is very high, possibly exceeding the design of the ATU or a balun.

should read: *It is harder on frequencies that are close to the even harmonics (2nd, 4th, …) of the fundamental. The antenna is once again resonant, however, its mainly resistive impedance is very high, even infinite, likely exceeding the design of the ATU or a balun, if fed in the centre. However, it may be successfully used with a different feed point location, closer to the ends, or with another matching device.*

Page 276 · Section 17.2
SWR and Power, last paragraph

Because this meter contains diodes, it should be placed before any final low-pass filters to supress harmonics.

should read: *Because this meter provides an SWR reading for the equipment it protects, it should be placed immediately after an amplifier, if one is used, or just after the transceiver, and before any final low-pass filters.*

IRTS HAREC
Amateur Radio Station Licence
Study Guide

Rafal Lukawiecki
Dave Moore · Jerry Cahill
Keith Crittenden · Mike Lee · Simon Kenny

Fourth Edition

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AMATEUR RADIO STATION LICENCE

Study Guide

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Study Guide

Fourth Edition

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for your patience and support

and to all who volunteer

for a good cause

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This guide is provided for class instructors and for individuals to help study for the *Harmonised Amateur Radio Examination Certificate* (HAREC) according to the requirements needed to obtain an Amateur Radio Station Licence in Ireland. It must be used in conjunction with the latest available regulations which may be newer than those referred to in this text. This guide is not designed for any other purpose.

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Contents

Tables xx

Abbreviations xxi

Foreword xxiii

Acknowledgements xxiv

1 Introduction 2

1.1 Welcome to Amateur Radio 2
1.2 About the IRTS 3
1.3 How to Use this Study Guide 4
1.4 How to Teach Using this Guide 5
1.5 Note to Licensed Readers 5

2 The Irish HAREC Amateur Station Licence Exam 8

Part A: Technical 11

3 Electrical and Electronic Principles 12

3.1 The Nature of Electricity 12
3.2 Dimensions, Units, and Metric Prefixes 13
3.2.1 Electrical, Electromagnetic, and Radio Dimensions and Units 13
3.2.2 Metric Prefixes 14
3.2.3 Examples of Unit Conversions 15

3.3 Current 16
3.3.1 Electricity & Current 16
3.3.2 Conductivity: Insulators and Conductors 16
3.3.3 Semiconductors and Solid-state Electronics 16
3.3.4 DC & AC Current 17

3.4 Sources of Electricity and Electromotive Force 17
3.4.1 Series vs. Parallel Connection 18

3.5 Voltage 19
3.6 Difference Between Electromotive Force and Voltage 19
3.7 Voltage and Current in Series and Parallel Circuits 20

3.7.1 Series Connected Circuit 20
3.7.2 Parallel Connected Circuit 21

3.8 Resistance 21
3.9 Ohm's Law 22
3.9.1 Ohm's Law Example 22

3.10 Electric Power and Energy 23
3.10.1 Electric Power 23
3.10.2 Power and Ohm's Law 24
3.10.3 Electrical Energy and Battery Capacity 26

4 Resistors in Circuits 28

4.1 Circuits 28
4.2 Resistors 28
4.2.1 Resistor Power Rating 29
4.2.2 Resistors Connected in Series 30
4.2.3 Resistors Connected in Parallel 30
4.2.4 Multiple Resistors in a Circuit 31
4.2.5 Worked Example: Current, Voltage, and Power with Multiple Resistors 32

5 Alternating Current and Sinusoidal Signals 38

5.1 Sinusoidal Signals 38
5.1.1 Amplitude 39
5.1.2 Period and Frequency 40
5.1.3 Wavelength and Frequency 40
5.1.4 Instantaneous and Average Values 42
5.1.5 rms, Effective Voltage, Peak-to-Peak Voltage, Power 42

5.2 Alternating Current 44
5.3 Phase 44
5.4 Harmonics 45
5.5 Modulated Sinusoidal Signals 45

6 Digital Signal Processing and Non-Sinusoidal Signals 48

6.1 Non-Sinusoidal Signals 48
6.2 Digital Signal Processing 51
6.2.1 Time and Frequency Domains 53
6.2.2 Fast Fourier Transform (FFT) 56

6.3 ADC, Sampling, and Quantisation 58
6.3.1 Sampling 58
6.3.2 Quantisation 59
6.3.3 Sampling Rate and Resolution 60
6.3.4 Minimum Sampling Rate 61
6.3.5 Oversampling 62

6.4 DAC and Direct Digital Synthesis 63
6.5 Software Defined Radio 64
6.5.1 SDR as a Broadband Receiver 65
6.5.2 Modern Transceivers and SDR 66

7 Radio Waves and Spectrum 70

7.1 Radio Waves and Electromagnetic Radiation 70
7.2 Electromagnetic Wave 71
7.3 Fields and Wave Formation 72
7.3.1 Force Fields 72
7.3.2 Static and Steady Motion Fields 73
7.3.3 Radiating Fields 74
7.3.4 Formation of the Wave 75
7.3.5 Propagating Electromagnetic Wave 80

7.4 Frequency 82
7.5 Radio Spectrum 83
7.6 Electric Field 85
7.7 Magnetic Field 85
7.8 Polarisation 86

8 Resonant Circuits and Components 88

8.1 Resonant Components: Inductors 88
8.1.1 Back Electromotive Force 89
8.1.2 Inductors in Series and Parallel 90
8.1.3 Inductive Reactance 91

8.2 Resonant Components: Capacitors 92
8.2.1 Dielectrics 94
8.2.2 Behaviour of Capacitors in AC and DC 94
8.2.3 Capacitors in Series and Parallel 95
8.2.4 Capacitive Reactance 96

8.3 Reactance, Resonance, and Impedance 98
8.3.1 Reactance 98
8.3.2 Resonance 98

8.3.3 Impedance 100
8.3.4 Impedance as a Number 101

8.4 Tuned Circuits, Filters, and Q Factor 102
8.4.1 Series and Parallel LC Circuits 102
8.4.2 Filters 106
8.4.3 Digital Filters 111
8.4.4 Q factor 112

8.5 Quartz Crystals 113
8.6 Oscillators 113
8.6.1 Resonant Circuit Oscillator 115

9 Power Ratios and Decibels 116

9.1 Decibel 116
9.2 Power Ratios 117
9.2.1 Power Ratios in Watts as Decibels 117
9.2.2 Power Ratios using Voltage or Current as Decibels 117

9.3 Absolute Power in Decibel-Watts 118
9.4 Effective Power 119

10 Other Components and Circuits 120

10.1 Diodes 120
10.1.1 Forward Voltage (Bias Voltage) 121
10.1.2 Peak Inverse Voltage 121
10.1.3 Leakage Current 121
10.1.4 Power Rating 121

10.2 Transistors 122
10.2.1 Currents and Biasing in a BJT 122
10.2.2 Amplification Factor 123
10.2.3 BJT vs FET 123

10.3 Valves (Thermionic Devices) 124
10.3.1 Triode 124
10.3.2 Valve Safety 125

10.4 Integrated Circuits 126
10.5 Transformers 127
10.5.1 Principle of Operation 127
10.5.2 Transformer Characteristics 127

10.6 Power Supplies 129
10.6.1 Voltage Transformer 129
10.6.2 Switched Mode Power Supply 130
10.6.3 Rectifier 130
10.6.4 Voltage Regulator (Stabiliser) 133

10.7 Amplifiers 134
10.7.1 Amplifier Characteristics 134
10.7.2 Classes of Power Amplifiers 135
10.7.3 Biasing 136
10.7.4 Distortion from Amplifier Non-Linearity 137
10.7.5 AF Amplifiers 138
10.7.6 RF Amplifiers 138

11 Modulation and Modes 140

11.1 Carrier, Signal, Modulation, Bandwidth, and Sidebands 140
11.2 Type of Modulation vs. Operating Mode 141
11.3 Analogue vs Digital: Type of Information Being Transmitted 142
11.3.1 Modulation of Analogue Information 142
11.3.2 Modulation of Digital Information: Bits and Symbols 143

11.4 Amplitude and Frequency Modulation 144
11.4.1 Amplitude Modulation 145
11.4.2 Frequency Modulation 151

11.5 AM (A3E) 156
11.6 SSB (J3E) 157
11.7 FM (F3E) 158
11.8 CW, ASK, OOK (A1A) 159
11.8.1 CW Modulating Signal (Keying Waveform) 160
11.8.2 CW Modulated Signal 160
11.8.3 CW Bandwidth and Rise and Fall Times 162
11.8.4 CW Sidebands 163

11.9 RTTY, FSK (F1B) 164
11.10 FT8, FSK (J2B, J2D) 166
11.11 PSK, 2-PSK, 4-PSK (G1B) 167
11.12 Other Modes 169

12 Transmitters 170

12.1 Output Power 171
12.2 Modulation Duty Cycle and Operational Duty Cycle 172
12.3 Output Impedance 173

12.4 Efficiency and Output Power 174
12.5 Problems Affecting Transmitters 174
12.6 CW Transmitter 175
12.6.1 CW: Master Oscillator 175
12.6.2 CW: Buffer/Driver 176
12.6.3 CW: Power Amplifier 176

12.7 SSB Transmitter 177
12.7.1 SSB: IF Signal Generation 178
12.7.2 SSB: Filter 178
12.7.3 SSB: Mixer 179
12.7.4 SSB: Linear Amplifier and Automatic Level Control (ALC) 179

12.8 FM Transmitter 180
12.8.1 FM: IF Signal Generation 181
12.8.2 FM: Frequency Multiplier 181
12.8.3 FM: Power Amplifier 182

12.9 Digital Modes 182
12.10 Modern Transmitters and SDR 183
12.10.1 Fully Digital Transmitter with RF DDS 184
12.10.2 Hybrid SDR Transmitter with IF DDS 185

12.11 Transverter 186
12.12 High Power Linear Amplifiers 186
12.13 HF Station 186

13 RECEIVERS 188

13.1 Superheterodyne Receiver 188
13.2 Double Conversion Superheterodyne Receiver 189
13.3 Receiver Components 190
13.3.1 RF Amplifier 190
13.3.2 Local Oscillator 190
13.3.3 Mixer 191
13.3.4 IF Filter 192
13.3.5 IF Amplifier 193
13.3.6 Detector (Demodulator) 194
13.3.7 Product Detector (CW and SSB) 195
13.3.8 FM Demodulator and Limiter 195
13.3.9 AF Amplifier 196
13.3.10 Automatic Gain Control (AGC) 196
13.3.11 S Meter 197
13.3.12 Squelch 198

13.4 SSB and CW Receiver 198
13.5 FM Receiver 198
13.6 Modern Receivers and SDR 199
13.6.1 Fully Digital Direct Sampling SDR Receiver 199
13.6.2 Hybrid SDR Receiver 201

13.7 Receiver Characteristics 202
13.7.1 Sensitivity and Signal-to-Noise Ratio (SNR) 202
13.7.2 Selectivity and Adjacent Channel Characteristics 202
13.7.3 Dynamic Range 203
13.7.4 Image Frequency and Image Rejection 203
13.7.5 Noise Figure and Factor 204
13.7.6 Stability 204
13.7.7 Desensitisation and Blocking 205
13.7.8 Intermodulation 205
13.7.9 Cross-modulation 205

14 TRANSMISSION LINES 206

14.1 Characteristic Impedance 206
14.2 Line Loss (Attenuation) 206
14.3 Velocity Factor 207
14.3.1 Electrical Length of a Line 208

14.4 Preventing Line Radiation 208
14.5 Parallel Lines 209
14.6 Coaxial Line 211
14.6.1 Coaxial Connectors 213

14.7 Waveguide 213
14.8 Common Mode Current 214
14.9 Impedance Matching and Transformation 215
14.9.1 Matched Case 216
14.9.2 Unmatched Case and Standing Waves 217
14.9.3 Standing Waves on a Transmission Line and Line Loss 218
14.9.4 Standing Wave Ratio (VSWR) 219

14.10 Antenna Tuning Units 220
14.11 Baluns and Chokes 221
14.11.1 Voltage vs. Current Baluns 222
14.11.2 1:1 Current Balun and Common Mode Choke 222
14.11.3 Voltage Baluns and Ununs 223

15 ANTENNAS 224

15.1 How do Antennas Work? 224
15.2 Near and Far Antenna Fields 224
15.3 Feed Point Impedance 227
15.4 Construction Materials 227
15.5 Far Field Pattern 228
15.5.1 Isotropic Antenna Radiation Pattern 228

15.6 Polarisation 229
15.7 Half-wave Antenna 229
15.7.1 Voltage, Current, and Impedance on a Half-Wave Antenna 229
15.7.2 Antenna Length 230

15.8 Half-Wave Dipole 231
15.8.1 Half-Wave Dipole Radiation Pattern 232
15.8.2 Vertically Oriented Dipole 234

15.9 Non-resonant Wire Antennas and Multiband Antennas 234
15.10 End-Fed Half-Wave Antenna 236
15.11 Folded Dipole 237
15.12 Trap Dipole 238
15.13 Quarter-Wave Ground Plane Antenna (Vertical) 238
15.13.1 Quarter-wave Vertical with Radials on the Ground 241
15.13.2 Quarter-wave Vertical with Elevated Radials (Counterpoise) 241

15.14 Yagi-Uda Antenna 242
15.14.1 Yagi Radiation Pattern 243

15.15 Directivity, Efficiency, and Gain 246
15.16 Front-to-Back Ratio 248
15.17 Capture Area (Effective Aperture) 249
15.18 Parabolic Antenna 249
15.19 Horn Antenna 250
15.20 Effective Power: EIRP and ERP 250
15.20.1 Calculating EIRP and ERP 251

16 PROPAGATION 254

16.1 Electromagnetic Wave 254
16.1.1 Propagation Velocity 254

16.2 Cycles and Solar Phenomena 255
16.2.1 Daily Cycle 255
16.2.2 Solar Cycle 256

16.2.3 Sunspots and Flares 257
16.2.4 Geomagnetic Storms and Auroras 257

16.3 Atmosphere 259
16.3.1 Troposphere 259
16.3.2 Ionosphere 259
16.3.3 Ionospheric Layers 259

16.4 Line-of-Sight Propagation and Radio Horizon 261
16.4.1 Free Space Attenuation 261

16.5 LF, MF, and HF Propagation Mechanism 262
16.5.1 Ground Wave 262
16.5.2 Sky Wave 263

16.6 LF and MF Propagation 263
16.7 HF Propagation 265
16.8 VHF and UHF Propagation Mechanisms 266
16.8.1 Tropospheric (Space) Wave 266
16.8.2 Troposcatter 266
16.8.3 Aircraft Scatter (Aircraft Reflection) 266
16.8.4 Tropospheric Ducting 267
16.8.5 Sporadic E 267
16.8.6 Auroral Reflection and Scattering 267
16.8.7 Meteor Scatter 267
16.8.8 Earth-Moon-Earth (EME) 268
16.8.9 Satellites 268

16.9 Fading 269
16.10 Estimating and Predicting Propagation 269
16.10.1 Critical Frequency 269
16.10.2 Maximum Usable Frequency (MUF) 269
16.10.3 Lowest Usable Frequency (LUF) 271

17 MEASUREMENTS 272

17.1 Multimeter, Ammeter, Ohmmeter, Voltmeter 272
17.1.1 Voltage 273
17.1.2 Current 273
17.1.3 Resistance 273

17.2 SWR and Power 274
17.3 Oscilloscope 276
17.4 RF Envelope 277
17.5 Spectrum Analyser 278

17.6 Signal Generator 278
17.7 Frequency Counter 279
17.8 Field Strength Meter 279
17.9 Antenna Analyser 280
17.10 Dummy Load 281

18 ELECTROMAGNETIC COMPATIBILITY, IMMUNITY, AND TRANSMITTER INTERFERENCE 282

18.1 Electromagnetic Compatibility 282
18.1.1 Radiated Emissions 282
18.1.2 Conducted Emissions 283
18.1.3 Interference and Immunity 283
18.1.4 Field Strength and EMC 283
18.1.5 Prevention 284

18.2 Transmitter Distortion and Spurious Emissions 287
18.2.1 Spurious Emissions 290

19 SAFETY 292

19.1 Radio Safety and The Irish Law 292
19.2 Equipment Labelling and Access Control Requirements 293
19.3 Electricity and The Human Body 293
19.3.1 Dealing with Electric Shock 293
19.3.2 RF Burns from Direct and Near Contact with RF Currents 294

19.4 Mains Power Supply 295
19.4.1 Supply Safety: Switches and RCDs 295
19.4.2 Protective Earth 296
19.4.3 Wiring and Plugs 297
19.4.4 Fuses 297
19.4.5 Valve Equipment and High Voltage Power Supplies 298
19.4.6 Adjusting Live Equipment 299

19.5 Mobile and Battery Safety 299
19.6 Antenna (Aerial) Safety 299
19.6.1 Mechanical Safety 299
19.6.2 Lightning 300

19.7 Chemicals 300
19.8 Non-Ionising Radiation and Electromagnetic Field Safety 300
19.8.1 Emissions and the Exposure Limits 301
19.8.2 How to Comply? 302
19.8.3 Nature of the Risks 303

19.8.4 Station Characteristics Influencing RF Emissions 305
19.8.5 Estimating and Modelling RF Field Strengths and Exposure 307
19.8.6 Interior of Transmitters and Power Amplifiers 310
19.8.7 Practical Suggestions 310

Part B: Operating Rules, Procedures and Regulations 313

20 ITU Radio Regulations 314

20.1 International Telecommunications Union (ITU) 314
20.2 ITU Radio Regions and the IARU 314
20.3 Purpose of the Amateur Service 315
20.4 Permitted Communications 315
20.5 Primary and Secondary Allocations 316
20.6 Emission Designators 316
20.7 Frequency of Identification 318

21 CEPT Regulations 320

21.1 CEPT and HAREC 320
21.2 CEPT Radio Amateur Licence 320
21.3 Prefix When Visiting a Country Implementing CEPT T/R 61-01 322
21.4 National Call Sign Prefixes 323

22 Irish Laws, Regulations, and Licence Conditions 326

22.1 Wireless Telegraphy Regulations 326
22.1.1 Who Can Use Your Station? 326

22.2 ComReg Amateur Station Licence Guidelines 326
22.3 Obtaining an Irish Amateur Station Licence 327
22.4 Licence Application, Duration, Amendments, Cancellation, Revocation 328
22.5 Club Licences 329
22.6 Special Events 329
22.7 Land Mobile 329
22.8 Maritime Mobile 330
22.9 Logbook Keeping 331
22.10 Additional Authorisations 331
22.11 Technical Requirements 331
22.12 CE Type Approval 332

23 Phonetic Alphabet 334

23.1 International Radiotelephony Spelling Alphabet 334

24 Call Signs 336

24.1 Allocation of Call Signs 336
24.2 Composition of Call Signs 336
24.3 Irish Call Signs 337
24.4 Call Sign Usage 337

25 Radio Spectrum Allocation in Ireland and IARU Band Plans 338

25.1 Spectrum Allocation in Ireland 338
25.2 Band Plans 339
25.3 Operational Bands 340
25.3.1 80 m Band Plan 341
25.3.2 Irish Regulations Regarding 60 m Band 342
25.3.3 Band Edges, Status, Power, Restrictions, Emergency Use 342
25.3.4 Propagation Beacons Frequencies 344
25.3.5 Emergency Centres of Activity Frequencies 344

26 Q-Codes and Abbreviations 346

26.1 Q-Codes 346
26.2 Q-Code as a Question or an Answer 348
26.3 Operational Abbreviations 348

27 International Distress Signs, Emergency and Natural Disaster Communications 350

27.1 Distress Signals 350
27.1.1 Radiotelegraphy (Morse) Distress Signal 350
27.1.2 Radiotelephony (Voice) Distress Signal 350

27.2 Emergency and Natural Disaster Communications 350
27.3 Emergency Frequencies 351
27.4 Role of Licensed Radio Amateurs in Emergency Communication 351
27.4.1 Communications Emergency 352
27.4.2 Served Agencies 352
27.4.3 Net 352
27.4.4 Who You Are Not 353
27.4.5 Day-to-Day vs. Emergency Communication 353
27.4.6 Means of Emergency Communication 354

27.5 Measures in Case of Emergency 354

28 Social Responsibility of Radio Amateur Operation and the Code of Conduct 356

28.1 Basic Principles 356
28.2 Danger of Conflict 357
28.3 How to Avoid Conflict? 357
28.4 The authority vs. Self-discipline in Amateur Radio 357
28.5 Amateur Radio Language 358
28.6 Listen 359
28.7 Use Your Call Sign Correctly 359

29 Operating Procedures and Non-Interference 360

29.1 How to Make a QSO 360
29.2 Content of Transmissions 361
29.2.1 Subjects to Avoid 361

29.3 Making Initial Calls 362
29.3.1 Selecting a Frequency 362
29.3.2 Format of a CQ Call 363
29.3.3 CQ Calls to Specific Geographic Areas 364
29.3.4 CQ DX 364
29.3.5 Format of an Initial Call to a Specific Station 365

29.4 Replying to Initial Calls 366
29.5 RST Code 367
29.6 Non-Interference 370
29.6.1 How to Deal with Spectrum Interference? 370

30 Further Reading 372

30.1 Technical Resources 372
30.2 Regulations and Guidelines 373

Illustration Credits 375

Edition History 378

Index 379

TABLES

1-A: Teaching plan suggestion 6
2-A: HAREC Exam Section A – Technical 9
2-B: HAREC Exam Section B – Rules, Procedures, Regulations 9
3-A: SI dimensions and units 14
3-B: Selected SI metric prefixes 15
3-C: Ohm's law formulae 22
7-A: ITU radio band names (subset: LF, MF, HF, VHF, UHF) 82
8-A: LC circuits in series and in parallel with a load 105
9-A: Decibels as ratios 117
9-B: Power in watts as dBW 118
10-A: Transformer characteristics and turns ratio 128
10-B: Power amplifier classes and their characteristics 136
11-A: Common operating modes and modulation schemes 142
12-A: Modulation duty cycles of common modulation types 173
13-A: Typical receiver IF filter bandwidths 193
15-A: Typical half-wave antenna lengths 231
20-A: Common ITU emission designators 317
21-A: National prefixes: selected European countries 323
21-B: National prefixes: UK entities 324
21-C: National prefixes: Canada and USA 324
23-A: International radiotelephony spelling alphabet: letters 335
23-B: International radiotelephony spelling alphabet: numbers 335
25-A: IARU R1 detailed 80 m band plan (effective 01 June 2016) 339
25-B: IARU R1 simplified 80 m band plan 342
25-C: Operational bands: edges, status, power, restrictions 343
25-D: Beacon exclusive frequencies 344
25-E: Emergency centres of activity used in Ireland 345
26-A: Q-Codes 346
26-B: Operational abbreviations 349
29-A: R values in RST 368
29-B: S values in RST 368
29-C: T values in RST 368
30-A: Image licensing and attribution 375
30-B: Edition history 378

Abbreviations

Common abbreviations are listed below, except for Q-Codes, which are explained in Table 26-A: Q-Codes and Table 26-B: Operational abbreviations on pages 346–349. Physical quantity symbols can be found in Table 3-A: SI dimensions and units on page 14. A complete list of all the key terms used in this guide is in the Index on page 379.

AC	Alternating Current
ADC	Analogue to Digital Converter
AF	Audio Frequency
AFSK	Audio Frequency Shift Keying
AGC	Automatic Gain Control
ALC	Automatic Level Control
AM	Amplitude Modulation
AMSAT	Amateur Radio in Space
AMTOR	Amateur Teleprinting Over Radio
APRS	Automatic Packet Reporting System
AREDN	Amateur Radio Emergency Data Network
AREN	Amateur Radio Emergency Network
ARRL	American Radio Relay League
ARSPEX	Amateur Radio Space Exploration
ASK	Amplitude Shift Keying
ATU	Antenna Tuning Unit
BFO	Beat Frequency Oscillator
BJT	Bipolar Junction Transistor
CAT	Computer Aided Transceiver
CB	Citizens Band
CD	Compact Disc
CE	European conformity [1]
CEPT	European Conference of Postal and Telecommunications Administrations [2]
CIO	Carrier Insertion Oscillator
CME	Coronal Mass Ejection
ComReg	Commission for Communications Regulation
CPR	Cardiopulmonary resuscitation
CQ	General call
CW	Continuous Wave
DAC	Digital to Analogue Converter
DC	Direct Current
DDS	Direct Digital Synthesis
DIY	Do It Yourself
DMR	Digital Mobile Radio
DSB	Double Sideband Amplitude Modulation with Full Carrier
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DX	Long distance
ECC	Electronic Communications Committee (of CEPT)
EFHW	End Fed Half-Wave
EI	Ireland (Mainland)
EIRP	Effective Isotropic Radiated Power
EJ	Ireland (Offshore)
ELCB	Earth Leakage Circuit Breaker
EMC	Electromagnetic Compatibility
EMCOMM	Emergency Communications
EME	Earth-Moon-Earth
EMF	Electromagnetic Field (see emf below)
emf	Electromotive Force (see EMF above)
ERP	Effective Radiated Power
EU	European Union
EV	Electric Vehicle
FET	Field Effect Transistor
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FM	Frequency Modulation
FSK	Frequency Shift Keying
FT8	Franke & Taylor 8
GPS	Global Positioning System
HAREC	Harmonised Amateur Radio Examination Certificate
HF	High Frequency
HI-FI	High Fidelity
IARU	International Amateur Radio Union
IARUMS	International Amateur Radio Union Monitoring Service
IC	Integrated Circuit
ICAO	International Civil Aviation Organization

1 Conformité européenne

2 Conférence européenne des administrations des postes et des télécommunications

ICNIRP	International Commission for Non-Ionising Radiation Protection
IF	Intermediate Frequency
IIR	Infinite Impulse Response
IMD	Intermodulation Distortion
IRTS	Irish Radio Transmitters Society
IT	Information Technology
ITU	International Telecommunication Union
LC	Inductive-Capacitive
LED	Light Emitting Diode
LF	Low Frequency
LO	Local Oscillator
LSB	Lower Sideband
LUF	Lowest Usable Frequency
MCB	Miniature Circuit Breaker
MF	Medium Frequency
/M	Mobile
/MM	Maritime Mobile
MP3	Moving Picture Experts Group Audio Layer 3
MUF	Maximum Usable Frequency
NATO	North Atlantic Treaty Organisation
NBFM	Narrow Band Frequency Modulation
NCO	Numerically Controlled Oscillator
NPN	N-type–P-type–N-type Transistor
OFCOM	Office of Communications (UK)
OOK	On-Off Keying
OSCAR	Orbiting Satellite Carrying Amateur Radio
PCB	Printed Circuit Board
PD	Potential Difference
PDF	Portable Document Format
PEP	Peak Envelope Power
PES	Principal Emergency Service
PIR	Passive Infrared
PIV	Peak Inverse Voltage
PLL	Phase Locked Loop
PM	Phase Modulation
PNP	P-type–N-type–P-type Transistor
PRA	Principal Response Agency
PSK	Phase Shift Keying
PSU	Power Supply Unit
PV	Photovoltaic
PVC	Polyvinyl Chloride
QAM	Quadrature Amplitude Modulation
RCD	Residual Current Device
RED	Radio Emissions Directive
RF	Radio Frequency
RFID	Radio Frequency Identification
rms	Root Mean Square
ROHS	Reduction of Hazardous Substances
RS	Readability and Strength
RSGB	Radio Society of Great Britain
RST	Readability, Strength, and Tone
RTTY	Radio Teletype
SAR	Specific Absorption Rate
SDR	Software Defined Radio
SI	International System of Units [3]
SNR	Signal to Noise Ratio
SOS	Distress signal
SSB	Single Sideband
SSTV	Slow-Scan Television
SWR	Standing Wave Ratio
T/R	Technical Recommendation
TN-C-S	Terra (Earth) Neutral Combined and Separated
TTY	Teletype
TV	Television
UHF	Ultra High Frequency
USB	Universal Serial Bus, *or,*
USB	Upper Sideband
UTC	Coordinated Universal Time
UV	Ultraviolet
VES	Voluntary Emergency Service
VFO	Variable Frequency Oscillator
VHF	Very High Frequency
VNA	Vector Network Analyser
VSWR	Voltage Standing Wave Ratio
WPM	Words per Minute
WSPR	Weak Signal Propagation Reporter

3 Système international

Foreword

AMATEUR RADIO is a journey and not a destination. This journey can take a lifetime to explore, and even then, you may well find that you have only scratched the surface of this wonderful hobby. To cram a lifetime of a learning experience into one book would be impossible, but what you have in your hands will open the gateway to your journey. For me, it started thirty years ago, and today I am still fascinated with all the technology and the friends that this hobby has brought my way.

Not everybody has the same strengths or learns the same way. However, amateur radio has something for everyone. For example, constructing a small homemade radio, or an antenna, and contacting another operator halfway around the world, knowing that it was your construction that made it happen, is a joy you will never forget. Decoding pictures from the space station, or sending your own TV signals, are only some of the many possibilities afforded to you when you obtain an amateur radio licence.

Rafal EI6LA is an experienced instructor and a renowned speaker, with a career in software and data science. Having recently taken the amateur radio licensing exam, he developed an appetite to understand every facet of the hobby. While eager to assist others to succeed, Rafal undertook the development of what is now this Study Guide.

Although the title of this book implies it is used for studying for the Irish amateur radio station licence, it is much more. I have no doubt that as you continue your journey you will pick it up many times as a reference source. Rafal, and his team at the National Short Wave Listeners Club have developed this guide over several years while successfully teaching the course, monitoring students' understanding of the subjects, improving, and simplifying the contents to what you now hold today. Evidence of their hard work can be seen in the considerable number of successful candidates who have been joining us on the airwaves.

I hope you will find benefit in the many hours of research that has gone into this fine publication and join us to see where your journey will lead.

Enda Broderick EI2II
President of the Irish Radio Transmitters Society

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The IRTS would also like to acknowledge and thank all its members and their affiliated clubs for their continued support and assistance.

IRTS HAREC

AMATEUR RADIO STATION LICENCE

Study Guide

1 Introduction

1.1 Welcome to Amateur Radio

AMATEUR RADIO is wonderful! The invisible radio waves let us connect with each other. The magic of radio propagation means that no matter where you are, any place on Earth, and in Space, even the Moon, and the Universe beyond, is within your reach.

Figure 1-i: Megan EI5LA and the author, Rafal EI6LA, studied for their licence together with the National Short Wave Listeners Club. They would like to wish you success in your studies. [Photo by Holger Lorenz EI3KM, see page 375]

Everyday radio communication is easy, thanks to modern mobile phones. However, there is so much more that can be done with just a piece of wire and a simple radio for those who wish to take up the challenge of getting an amateur radio licence.

While you are studying for the exam, you should listen to the bands. Hear the spoken conversations, get mesmerised by the sound and rhythm of Morse code, listen to the far away propagation beacons, receive radiotelegraphic broadcasts of weather reports, decode digital radio transmissions, or see images sent from the International Space Station using a simple receiver and your computer. Even before you get your first radio you can use thousands of free, online receivers, such as publicly shared web Software Defined Radios (SDR) and hear the signals from anywhere on the planet. You can start experimenting with antennas and be amazed how a simple wire can hear what is being transmitted on the other side of the globe, as far as Australia or New Zealand.

Where will amateur radio take you? Will you chat and make new friends on the air – or, as we say, *ragchew* with them? Will you become as skilled in operating a Morse key as telegraphists did over a hundred years ago? Or will you prefer to speak into a microphone? Will you type messages on a keyboard of a computer connected to another other one using nothing but the radio waves? Will you learn to solder and build your own transceivers, antennas, and other equipment? Or will you restore historical equipment? Will you devise new digital modes of communication that can hear the quietest signals despite the noise or interference? Will you try and contact every county in Ireland, and every country in the world? Will you participate in and win radio contests? Will you chase awards? Will you use satellites orbiting above the

planet? Will you build a station and develop skills to help your community during emergencies? Will you conduct research to further our understanding of how it all works? Will you, one day, help newcomers learn about what excited you in radio to get them started?

Enjoy discovering radio while you study for the Harmonised Amateur Radio Examination Certificate, HAREC. The lessons will not stop when you earn it. The real learning starts as soon as you get on the air for the first time. You will meet knowledgeable, passionate, both the experienced and those still quite new, but ever so helpful radio amateurs. Without a doubt, you will make many lifelong friends, no matter where they live.

Thank you for picking up this book. The authors and the editors of this guide welcome you warmly on the exciting journey that you have just begun. Good luck with the exams – and good propagation!

1.2 About the IRTS

The Irish Radio Transmitters Society, www.irts.ie, is Ireland's national society affiliated with the International Amateur Radio Union, IARU, www.iaru-r1.org. This Study Guide has been published by the IRTS.

Our most important function, since the beginnings in 1932, has been to represent radio amateurs to protect and to grow their worldwide rights.

With the help of a network of IRTS affiliated clubs,[4] we promote the study and the enjoyment of amateur radio, and we work to secure its future in Ireland. We offer essential services to support our members, including the Irish QSL card bureau,[5] an in-depth, printed quarterly magazine *Echo Ireland*,[6] a shorter, monthly magazine *EI News* distributed by email, a weekly on-air news service,[7] a members-only email reflector and a discussion forum,[8] and *much* more!

By joining and supporting us you will help protect our rights, especially the never-ending effort to maintain our access to the *radio spectrum* that radio amateurs have used since 1927. That spectrum is worth trillions of euros to commercial operators. If we do not protect it, we *will* lose it.

When you are ready, you can assist us by becoming a society officer, or a member of the IRTS committee. We welcome enthusiastic new amateurs to help our worldwide community by joining in our active role within the IARU.

We encourage inclusion, diversity, and active participation on the air, to keep growing, and to remain relevant for the future generations of radio amateurs.

Join us at irts.ie/join.

4 irts.ie/clubs
5 irts.ie/qslinfo
6 irts.ie/echoireland and see the archive of issues dated from 1948.
7 Sign up at irts.ie/getweeklynews. The on-air broadcast schedule is at irts.ie/bulletins.
8 irts.groups.io

1.3 How to Use this Study Guide

You can use this guide to study on your own, or while attending a taught course aimed at the Irish HAREC syllabus. IRTS members and affiliated clubs, and other organisations, provide such training. Find out about the courses at irts.ie/study.

There are two parts in this guide: Part A is technical, while Part B covers operating rules, procedures, and regulations. We recommend that you study the two parts in parallel. It will let you take a break from one area whilst learning the other. Both parts have chapters which match the exam sections as much as possible. Some exam topics are explained in a different order to where they appear on the exam paper because to learn one you need to learn another one first. For example, to learn some aspects of the electromagnetic theory you need to learn about fundamental components, such as resistors, inductors, and capacitors. For those reasons the order of the sections in this guide follows a more natural learning order rather than the order of the exam. Some of the exam topics have been further split in this book. For example, the exam section *Antennas and Transmission Lines* is presented as two separate chapters in this guide: first, you will learn about transmission lines, then about antennas – it flows better this way when studying.

You can find the Irish HAREC exam syllabus at irts.ie/exam. When you reach the end of this guide you will have learned everything needed to pass it because this guide is based on it. You will have also learned the essentials needed to get on the air.

Everything in this guide is related to the exam syllabus, with two exceptions:

1. Text explicitly marked as *not for the purposes of the exam,* including a handful of sections labelled that way. They provide background information that should help you understand a more complex subject. You can skip those additional explanations if you are not finding them helpful.
2. Text in the footnotes,[9] at the bottom of the pages, provides further detail, historical references, or information useful to a radio amateur, especially when making your first steps, but which is not related to the exam syllabus. To read this guide more quickly, or when revising, skip all the footnotes.

When an important concept is introduced for the first time, or if it is reintroduced in a new context, it is highlighted using SMALL CAPITALS and it is listed in the Index on page 379 at the back of the guide. Prior to the exam, use the Index to check if there are any terms that you should revise.

Abbreviations are usually explained only the first time they appear in the book. You may want to bookmark the list of abbreviations on page xxi.

If you are reading the PDF edition of this guide, all links, page numbers, chapter, section, figure, and table numbers are marked green. They are active and can be clicked on if your PDF reader supports such functionality. They will help you navigate the guide. If you are reading the printed edition, use the Table of Contents on

9 This is a *footnote*. There are 469 such footnotes in this guide. Anything in a footnote is for your reference, to help you learn, or to provide background information – but it is *not* part of the exam syllabus.

page vii or the Index to find the topics. To navigate the printed pages, you can also use the running footer at the bottom of each page. The current chapter is shown on the left, and the section number and title appear on the right.

To purchase a printed copy, or to download the free PDF, visit irts.ie/guide. Each edition has been formatted to suit its medium, however, the contents is the same.

1.4 How to Teach Using this Guide

If you are using this guide for teaching the HAREC syllabus, you should plan, in advance, what subjects to discuss during each teaching session to allow your students to prepare. Students should study the relevant section in advance of a class, and again, after each class, and once more, a few days or a week prior to the exam.

The current experience of the National Short Wave Listeners Club,[10] who wrote this Study Guide and who teach using it, suggests that it is necessary to allocate approximately twenty-three teaching sessions, each two-hour long, to cover the syllabus. However, this amount of time would not allow the teachers to cover each topic in as much detail as provided in the guide. Self-study, prior and after each class, is essential.

A proposed teaching plan is shown in Table 1-A on the next page. Most of the two-hour sessions have been divided into two parts, to cover different subjects, to maintain the interest level, and to ensure that both the technical, part A, and the regulatory, part B, of the HAREC syllabus are introduced in parallel throughout the course.

The durations of each part of each session are not always even. The table suggests when one part needs to be longer than another. For example, session 1 takes about 30% of the class time to explain how to study, with the rest focused on regulations. Session 6 uses about 90% of the time to cover AC, and only 10% to discuss call sign usage. On the other hand, session 7 is evenly split between its topics.

As a teacher, you will need to adjust the plan to accommodate different groups of students, or even devise your own schedule. We would welcome your feedback on our suggestion, and we would like to hear about the experience of anyone using our guide for teaching HAREC around the world.

1.5 Note to Licensed Readers

Already licensed readers may want to skip the introductory Chapters 3–5, 7–10, and focus on the newer material. More recent developments can be found in Chapters 6, 11, and in 12.10, and 13.6. Transmission line treatment in 14, and some illustrations in 15 and 16, may shed a fresher perspective on the perennial subjects. Safety section 19.8 is new and of increasing relevance. Regulations are covered in 20–29, and change often. For the curious, section 7.3 may be of interest, as it includes an insight into the nature of radio wave formation. We welcome your comments and feedback.

10 swl.ie

Table 1-A: Teaching plan suggestion

Session	First hour	Second hour
1	Welcome Meet Your Tutors How to Study	20 ITU Radio Regulations 21 CEPT Regulations 22 Irish Laws, Regulations, and Licence Conditions
2	3.1 The Nature of Electricity 3.2 Dimensions, Units, and Metric Prefixes 3.3 Current 3.4 Sources of Electricity and Electromotive Force 3.5 Voltage 3.6 Difference Between Electromotive Force and Voltage 3.7 Voltage and Current in Series and Parallel Circuits	22 Irish Laws, Regulations, and Licence Conditions
3	3.8 Resistance 3.9 Ohm's Law 3.10 Electric Power and Energy	23 Phonetic Alphabet
4	4 Resistors in Circuits	24.1–24.3 Call Signs
5	5 Alternating Current and Sinusoidal Signals	6.1 Non-Sinusoidal Signals
6	6.2 Digital Signal Processing 6.3 ADC, Sampling, and Quantisation 6.4 DAC and Direct Digital Synthesis 6.5 Software Defined Radio	24.4 Call Sign Usage
7	7 Radio Waves and Spectrum	25 Radio Spectrum Allocation in Ireland and IARU Band Plans
8	8.1 Resonant Components: Inductors 8.2 Resonant Components: Capacitors	26 Q-Codes and Abbreviations
9	8.3 Reactance, Resonance, and Impedance	27 International Distress Signs, Emergency and Natural Disaster Communications
10	8.4 Tuned Circuits, Filters, and Q Factor 8.5 Quartz Crystals 8.6 Oscillators	28.1 Basic Principles 28.2 Danger of Conflict 28.3 How to Avoid Conflict? 28.4 The authority vs. Self-discipline in Amateur Radio

Session	First hour	Second hour
11	9 Power Ratios and Decibels	10.1 Diode 10.2 Transistor 10.3 Valves (Thermionic Devices) 10.4 Integrated Circuits
12	10.5 Transformers – 10.6 Power Supplies	10.7 Amplifiers
13	11 Modulation and Modes	
14	12 Transmitters: 12.1 Output Power 12.2 Modulation Duty Cycle 12.3 Output Impedance 12.4 Efficiency 12.5 Problems Affecting Transmitters 12.6 CW Transmitter 12.7 SSB Transmitter	28.5 Amateur Radio Language 28.6 Listen 28.7 Use Your Call Sign Correctly
15	12.8 FM Transmitter 12.9 Modern Transmitters and SDR 12.11 Transverter 12.12 High Power Linear Amplifiers 12.13 HF Station	29.1 How to Make a QSO 29.2 Content of Transmissions
16	13 Receivers	29.3 Making Initial Calls
17	14 Transmission Lines	29.4 Replying to Initial Calls 29.5 RST Code
18	15 Antennas: 15.1 How do Antennas Work? – 15.9 Non-resonant Wire Antennas and Multiband Antennas	
19	15.10 End-Fed Half-Wave Antenna – 15.20 Effective Power: EIRP and ERP	29.6 Non-Interference
20	16 Propagation	
21	17 Measurements	18 Electromagnetic Compatibility, Immunity, and Transmitter Interference
22	19.1 Radio Safety and The Irish Law – 19.7 Chemicals	19.8 Non-Ionising Radiation and Electromagnetic Field Safety
23	Final Q&A	Exam Hints and Tips

2 The Irish HAREC Amateur Station Licence Exam

The current Irish HAREC exam consists of 60 questions in two sections, A and B, each containing 30 questions. The pass mark is 60% and a pass is required in *each* of the two sections of the paper. This means that you need to have at least 18 correctly answered questions in each section to pass the exam. If you fail one of the sections but pass the other, you will need to take the entire exam again – no partial credits are allowed. The exam lasts two hours.[11]

If you have physical or other impairments, such as those outlined in the *Irish Disability Act 2005*, you should contact the IRTS Examination Board to discuss any special arrangements needed to facilitate you during the exam. See irts.ie/contactus.

The tables below show the structure of the exam: the topic and the number of questions in each subsection of the exam. You can also see the chapter number and the page number where the corresponding subjects are explained in this guide. The order of the topics in this guide does not always follow their exam order. Instead, topics are presented in the recommended learning order.

You can download a sample exam paper from irts.ie/downloads.

11 Irish HAREC exam information current as of January 2024.

Table 2-A: HAREC Exam Section A – Technical

	Exam section A topics	Questions	Chapter	Page
A1	Safety	5	19	292
A2	Interference and Immunity	4	18	282
A3	Electrical, Electromagnetic, and Radio Theory	4	3 5 · 6 · 7 11	12 38 · 48 · 70 140
A4	Components and Circuits	3	4 · 8 9 · 10	28 · 88 116 · 120
A5	Transmitters and Receivers	4	11 12 · 13	140 170 · 188
A6	Antennas and Transmission Lines	4	15 14	224 206
A7	Propagation	4	16	254
A8	Measurements	2	17	272

Table 2-B: HAREC Exam Section B – Rules, Procedures, Regulations

	Exam section B topics	Questions	Chapter	Page
B1	Phonetic Alphabet	1	23	334
B2	Q-Codes	3	26	346
B3	International Distress Signs, Emergency Traffic and Natural Disaster Communications	3	27 · 25	350 · 338
B4	Call Signs	3	24	336
B5	Radio Spectrum Allocation in Ireland and IARU Band Plans	4	25	338
B6	Social Responsibility of Radio Amateur Operation and the Code of Conduct	3	28	356
B7	Operating Procedures and Non-Interference	5	29	360
B8	ITU Radio Regulations	2	20	314
B9	CEPT Regulations	3	21	320
B10	Irish Laws, Regulations, and Licence Conditions	3	22	326

(*This page left blank to match the numbering in the printed edition*)

Part A: Technical

3 Electrical and Electronic Principles

FOUR EXAM QUESTIONS · SECTION A3

This chapter introduces the fundamental principles of electricity and electronics. You will study three essential concepts: current, voltage, and resistance, and Ohm's law which explains how they relate to each other. You will also learn about sources of electricity and different ways of connecting components together to create electronic circuits. There are many key topics in this chapter. Study them carefully, as their good understanding will make the next few chapters easy to follow.

3.1 The Nature of Electricity

To understand the principles of electricity and electronics it is useful to know something about the structure of the ordinary matter that surrounds us. *Things* such as rocks, liquids, gasses, metals, people, stars, and planets are made of ATOMS.

Atoms are very small. There are billions and billions of them in even the smallest things. However, atoms are made of even smaller *subatomic particles.* Among such subatomic particles there are two that are of particular interest to us.

One is called a PROTON. Protons sit at the centre of atoms. Around a proton, moving in a somewhat circular orbit, is the second subatomic particle we are interested in, called an ELECTRON, after which the word electricity is named.[12] The proton has what is known as a positive ELECTRIC CHARGE (+) and the electron has a negative electric charge (−). Electrons and protons are also known as CHARGE CARRIERS.

Electrical wires are made of conductors. An example of a conductor is a metal called copper. All ordinary matter is made of a great many atoms. Electrical wiring is made of an enormous number of copper atoms.

To somewhat oversimplify, it could be said that in metals some electrons can move from one atom to another if a suitable force is applied. Electrons are, therefore, the primary charge carriers in metal conductors. The atoms in a metal are all next to each other. If a sufficiently high electromotive force is applied to one side of the material, then electrons in one atom will pass, or jump, into the adjacent atom.

As each electron moves into its adjacent atom this produces a flow of electrons, and of their electrical charges, rather like a flow of water through a hose pipe. This flow of charge carriers, like electrons in a metal, is known as ELECTRIC CURRENT.

12 Before electron became the name of the subatomic particle, the original meaning of the word, *electrum* in Latin, referred to a type of fossilised resin known as *amber.* When amber is rubbed, it becomes charged with static electricity and attracts other objects, such as paper and hair.

3.2 Dimensions, Units, and Metric Prefixes

3.2.1 Electrical, Electromagnetic, and Radio Dimensions and Units

Symbols made up from letters of the Latin, and sometimes the Greek alphabets, are used to write and describe electrical and other physical phenomena and their physical quantities. Each quantity is usually referred to using two different symbols. One is known as the dimension, or as the DIMENSION SYMBOL. It is used to describe the physical phenomenon, such as electrical current. You will see it in equations and in formulae that describe the phenomenon, for example in the formula for the Ohm's law. The other very important symbol is known as the unit, or the UNIT SYMBOL, which is a measure of the amount of the physical quantity. Rarely, the same letters are used for both the dimension and the unit. Normally, they are different.

Historically, there were many different systems of units of measurement of physical quantities. Only one system is dominant at present. It is known as SI,[13] or the INTERNATIONAL SYSTEM OF UNITS. You are already familiar with it: *seconds, metres,* and *kilograms* are part of SI. While some people still prefer to talk about pounds, miles, furlongs, or inches, thankfully, in electronics and radio it is unusual to use anything other than the SI units, with only a couple of exceptions made for reasons of convenience.

For the purposes of the exam, you must know those letters, that is, the dimension symbols and the units for the most important electrical, electromagnetic, and other quantities that are useful in radio theory. They are shown in Table 3-A on page 14.

For example, the dimension symbol that we use to write about electrical current is the capital letter I. The quantity of an electric current is measured using a unit known as AMPERE,[14] often shortened to an AMP and abbreviated with the symbol A. Informally, you can think of amps like you think about the volume of water that is flowing in a river.

The table on the next page shows the physical units that you must know for the purposes of the exam. Be careful to remember if a lowercase or an UPPERCASE letter is used: 1 Hz is correct, but 1 hz is incorrect – the H must be capitalised in this particular symbol. A mistake is often made with the unit of time, second. Lowercase s is correct, while uppercase S is not.[15]

13 Learn about SI at en.wikipedia.org/wiki/International_System_of_Units.

14 Named after French mathematician and physicist André-Marie Ampère, who is considered one of the fathers of the science of electromagnetism. The full unit names are always written in lower case, even if they are named after a person, hence *ampere* and not *Ampere*. However, the unit symbols for the units named after people are written in capitals. The symbol for ampere is A, and not *a*.

15 Uppercase S is the unit symbol of a *siemens,* a physical quantity of conductance.

Table 3-A: SI dimensions and units

Physical quantity	Dimension symbol	Unit	Unit symbol
Current	I	ampere	A
Electromotive Force (emf)	E or $\mathcal{E}$ [16]	volt	V
Voltage or Potential Difference	V or E	volt	V
Power	P	watt	W
Energy	W [17]	kilowatt-hour [18]	kWh
Electric charge	q [16]	ampere-hour [19]	A·h
Resistance	R	ohm	Ω
Inductive Reactance	X_L	ohm	Ω
Capacitive Reactance	X_C	ohm	Ω
Reactance	X	ohm	Ω
Impedance	Z	ohm	Ω
Inductance	L	henry	H
Capacitance	C	farad	F
Frequency	f	hertz	Hz
Wavelength	λ (lambda)	metre	m
Length	l [20]	metre	m
Time	t	second	s

3.2.2 Metric Prefixes

Most of the units used in radio are either very large or very small numbers. To avoid writing many zeros, which leads to mistakes, it is common to use a METRIC PREFIX. The table below shows the metric prefixes most frequently used in radio.

For example, it is easier to remember that the weekly IRTS news service takes place on the frequency of 3650 kHz (kilohertz) than to remember it as 3 650 000 Hz (hertz). Some people prefer to remember it as 3.650 MHz (megahertz). Those are equivalent ways of saying the same, just like we know that 1 kg (kilogram) is a more convenient

16 You do *not* need to know the *dimension* symbols E or $\mathcal{E}$ (epsilon), or q, but you *do* need to know the *unit* symbols V and A·h for the exam.

17 There are other dimension symbols of *energy:* U and E. W is also used to represent the related concept of *work*. For the purposes of the exam, you only need to know W.

18 Although kilowatt-hour is a metric unit of energy, it is not an SI unit, because the *hour* h is not an SI unit – SI uses *seconds* s. Besides, the SI unit of energy is the *joule,* with a symbol J. However, in electrical and radio theory kWh is in common use. 1 kWh = 3.6 MJ. You only need to know the kWh.

19 Like kWh, the A·h is not an SI unit of electric charge. However, you need to know it as it is in common use for radio and electrical purposes. The SI unit of electric charge is the *coulomb,* symbol C. 1 A·h = 3600 C. You do not need to know the coulomb for the exam.

20 The dimension symbol is usually a capital letter, such as I for current, or L for length. It is related to SI system's *typical symbols for quantity,* usually a lowercase letter, such as i for current and l for length. This guide does not differentiate between them and uses the more frequently used ones, such as I (not i) for current, and l (not L) for length.

way of expressing weight than 1 000 g (gram). The metric prefix k (kilo) simply means *one thousand* of something else: grams, hertz, bytes, ohms, etc.

Similarly, there are metric prefixes for expressing very small quantities, such as m (milli) to say a *one-thousandth* of something else, for example, 1 mm (millimetre) is one-thousandth of a metre, 0.001 m.

It is frequently necessary to convert quantities that use different prefixes, such as kilo and mega, but of the same dimension, for example, length or resistance, to the *same* prefix before you can perform calculations. For example, to add 2 metres to 500 millimetres it is necessary to convert them all to the same prefix. You can choose which one to use. Let's say we want to convert millimetres to metres. In that case 500 mm becomes 0.5 m, because there are 1000 millimetres in 1 metre, and the sum of the two is 2.5 m. You will find it necessary to perform such conversions when working with resistance in kΩ and MΩ, or with frequencies, such as kHz and MHz.

The table below shows the SI metric prefixes that you need to know for the purposes of the exam. Be careful to remember if the letter is lowercase or uppercase, as they may have an opposite meaning. For example, the lowercase m is milli while uppercase M is mega. A common mistake is made with k for kilo: note the lowercase k, hence kHz is correct, while KHz is incorrect.

Table 3-B: Selected SI metric prefixes

Prefix	**Symbol**	**Factor**	**Decimal**	**Power of 10**
giga	G	One thousand million	1 000 000 000	10^{9}
mega	M	One million	1 000 000	10^{6}
kilo	k	One thousand	1 000	10^{3}
none		One	1	10^{0}
deci	d	One tenth	0.1	10^{-1}
centi	c	One hundredth	0.01	10^{-2}
milli	m	One thousandth	0.001	10^{-3}
micro	µ	One millionth	0.000 001	10^{-6}
nano	n	One thousand millionth	0.000 000 001	10^{-9}
pico	p	One million millionth	0.000 000 000 001	10^{-12}

3.2.3 Examples of Unit Conversions

$1\text{ mm} = 1/1000\text{ m} = 0.001\text{ m}$
$1000\text{ mm} = 1\text{ m}$

$1\text{ mV} = 1/1000\text{ V} = 0.001\text{ V}$
$1000\text{ mV} = 1\text{ V}$

$500\text{ mV} + 2.5\text{ V} = \ ?\text{V}$
$500\text{ mV} = 500 \times 0.001\text{ V} = 0.5\text{ V}$
$0.5\text{ V} + 2.5\text{ V} = 3\text{ V}$

$1\text{ km} = 1000\text{ m}$
$1\text{ m} = 1/1000\text{ km} = 0.001\text{ km}$

$1\text{ k}\Omega = 1000\ \Omega$
$1\ \Omega = 1/1000\text{ k}\Omega = 0.001\text{ k}\Omega$

$1.5\text{ k}\Omega + 750\ \Omega = ?\text{ k}\Omega$
$1.5\text{ k}\Omega = 1500\ \Omega$
$1500\ \Omega + 750\ \Omega = 2250\ \Omega$

3.3 Current

3.3.1 Electricity & Current

Let's summarise the discussion from sections 3.1 and 3.2.1. Movement of charge carriers, such as negatively charged electrons, constitutes an electric current. Even though the electrons flow from the negative to the positive TERMINAL (connector, end) of the source of electricity, by convention, it is said that the current, also known as CONVENTIONAL CURRENT, flows from the *positive* to the *negative* terminals.

The letter I is the dimension symbol of electric current. The unit of current is the ampere, A, commonly abbreviated to an amp.

3.3.2 Conductivity: Insulators and Conductors

In some substances electrons cannot move easily from one atom to another. They have a high resistance to the flow of the current and they are called INSULATORS. Examples of insulators are glass, acrylic (Perspex), rubber, mica, most plastics, oil, air, and distilled water. Some types of insulators have additional properties, which are discussed in section 8.2.1 Dielectrics.

Other substances have a low resistance to the flow of current, and they are called CONDUCTORS. Examples are metals, carbon, and some liquids, for example, acid solutions, electrolytes, and salt water. Almost all metals are good conductors.[21] They include silver, copper, gold, aluminium, iron, and mercury.

3.3.3 Semiconductors and Solid-state Electronics

A SEMICONDUCTOR is a substance whose resistance to the flow of the electric current can be varied between that of a good conductor and a good insulator. The best-known example of a semiconductor is a crystalline material known as SILICON. Manufacturing process changes it into either an n-type or a p-type semiconductor.[22] By sandwiching p-type and n-type materials together, SEMICONDUCTING JUNCTIONS are created. Those junctions have interesting electrical properties. For example, the flow of a current through an p-n junction depends not only on the voltage but also on the direction in which the current wants to flow. This principle is used to create one of the simplest, yet very important semiconducting components: a diode, see section 10.1.

Semiconductors form the basis of most modern electronic devices. More complex electronic components, including transistors, can be made by combining different types of semiconductors. In turn, almost every other device is made from them.

21 *Bismuth* and *tungsten* are examples of metals that are not good conductors. They are not part of the exam syllabus.

22 These two most important semiconductor materials differ in the primary charge carriers which they contain: electrons in n-type, and so-called *holes,* formed by the absence of electrons, in p-type. A p-n junction is made by joining them. Its behaviour is the foundation of modern electronics.

Devices made from semiconductors are also known as SOLID STATE devices. Solid-state electronics has followed in the footsteps of an earlier electronic technology based on *valves,* also known as *vacuum tubes,* explained in section 10.3 Valves (Thermionic Devices).[23] Even though valves are still used in radio, modern radio equipment is predominantly solid-state.

3.3.4 DC & AC Current

DIRECT CURRENT, or DC, travels only in *one* direction. The direction of the current is constant. The direction does not vary with time, but the amount of current can change over time. For example, batteries provide DC. The current from a battery will remain relatively constant until the battery starts to lose its charge.

ALTERNATING CURRENT, or AC, reverses its polarity, which means that it travels back and forwards. It changes its direction many times. For example, the AC current in a domestic Irish socket changes its direction from forwards to backwards, and back to forwards. This full cycle of two changes of the direction is completed 50 times per second. In other words, domestic AC has a frequency of 50 Hz (hertz). The sinusoidal nature of AC will be discussed in Chapter 5 Alternating Current and Sinusoidal Signals.

3.4 Sources of Electricity and Electromotive Force

Devices such as batteries and power supplies are VOLTAGE SOURCES. They provide the *push* necessary to maintain the flow of the current. This push is known as source voltage and is also called an ELECTROMOTIVE FORCE AND referred to as **emf**. Please note the lowercase spelling of emf, as opposed to uppercase EMF which is an abbreviation of Electromagnetic Fields, which will be introduced in Chapter 7.

The dimension symbol of the ELECTROMOTIVE FORCE that causes the electrical current to flow is the Greek letter $\mathcal{E}$ (epsilon) and sometimes letter E.[24] The quantity of this force is measured using a unit called a VOLT, abbreviated to V.[25] The same unit, volt, and its symbol V are also used to measure another important electrical phenomenon known as VOLTAGE, discussed later.

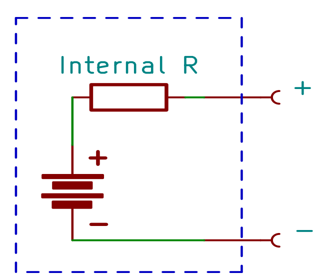

Figure 3-i: Internal resistance of a voltage source. [EI9ILB]

Voltage and current from a battery will get lower as the battery discharges itself over time. That time depends on the battery's capacity, see section 3.10 Electric Power and Energy. A practical voltage source

23 Transistors and solid-state electronics became practical and popular in 1960s, even though the first working transistor was made in 1947 by Bell Telephone Labs in USA. Before transistors, all electronic equipment that required signal amplification – a fundamentally important function – relied on valves (vacuum tubes) which were invented in 1907 by Lee de Forest, an early American radio pioneer.

24 For the purpose of the exam, you do not need to know the dimension symbols of electromotive force.

25 Named after Italian physicist Alessandro Volta.

has an INTERNAL RESISTANCE which limits the available current and causes a voltage drop when connected to a LOAD, i.e., a device that consumes electricity, such as a light bulb. This can be illustrated by showing a symbol representing an internal resistor next to the symbol of a voltage source. In this figure, the resistor is shown on top of the circuit.

This internal resistance will limit the total current to the SHORT CIRCUIT CURRENT if the device is short-circuited. Short circuit happens if the two terminals of the voltage source are joined to each other using a conductor, such as a piece of a wire, without connecting a load between them.

The output TERMINAL VOLTAGE of the voltage source is equal to the emf when not connected to a load, and once connected, dropping as the current is drawn.

3.4.1 Series vs. Parallel Connection

When voltage sources are connected in SERIES the total source voltage is the *sum* of the individual voltages. The circuit diagram shown in Figure 3-ii shows two voltage sources connected in series, that is, the positive terminal of one is connected to the negative terminal of another.

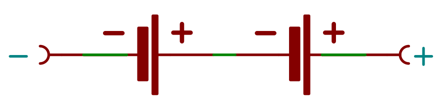

Figure 3-ii: Two voltage sources connected in series. [EI9ILB]

When voltage sources are connected in PARALLEL the source voltage across each will be the *same*. However, the current capacity is increased as current drain is shared between the sources. The circuit diagram in Figure 3-iii shows two voltage sources connected in parallel, that is, the positive terminals of the voltage sources are connected to each other, and the negative terminals are connected to the negative terminals.

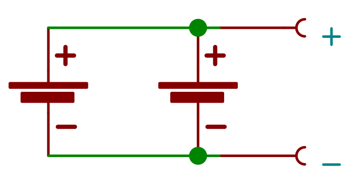

Figure 3-iii: Two voltage sources connected in parallel. [EI9ILB]

Caution is needed if voltage sources are to be connected in parallel as small differences in terminal voltage may cause a circulating current between the sources, dependent on their internal resistances.[26]

26 If the differences are large, this can yield unexpected effects and it can even damage some batteries.

3.5 Voltage

To keep a current flowing in a circuit, a difference in the electric "pressure" must be maintained between the ends of a circuit. This "pressure" is formally known as the ELECTRIC POTENTIAL. The POTENTIAL DIFFERENCE (PD) between any two points in the circuit is known as the VOLTAGE.

The letters *V* and *E* are the dimension symbols for voltage. Letter *E* is more frequently seen in American publications while letter *V* is usually used in Europe. The unit of voltage is the VOLT, whose unit symbol is also the letter V.

3.6 Difference Between Electromotive Force and Voltage

As already mentioned, volt is the unit of the electromotive force (emf) and of PD (voltage). The difference between emf and PD is subtle and depends on whether the current is or is not flowing in the circuit. Electromotive force, emf, is equal to the terminal (source) PD when no current flows. It represents the electrical potential ("pressure") that the source could exert if the current was not flowing. This is illustrated in Figure 3-iv, which shows that the device used to measure the emf, the voltmeter, must have a high internal resistance in order to prevent any significant current from flowing through the meter, affecting the measurement.

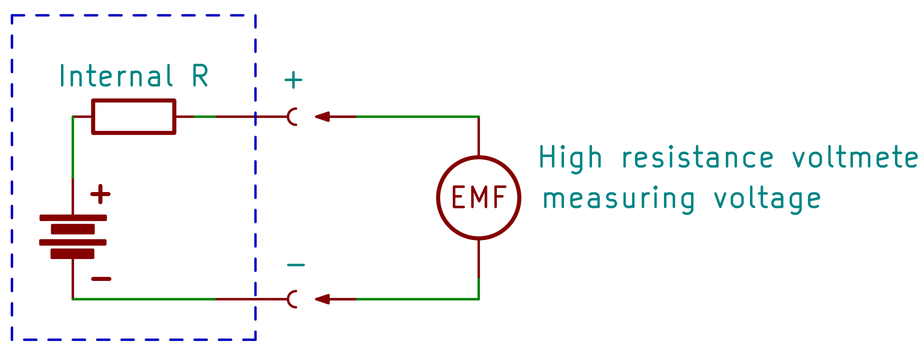

Figure 3-iv: Measuring electromotive force of a voltage source. [EI9ILB]

PD, however, is usually measured between any two points in a closed circuit through which the current *is* flowing. This is illustrated in Figure 3-v. The voltmeter used to measure PD must also have a high internal resistance in order not to divert a significant current away from flowing through the two points whose difference is being measured. In line with the general practice, this guide will refer to PD using its more common name, voltage.

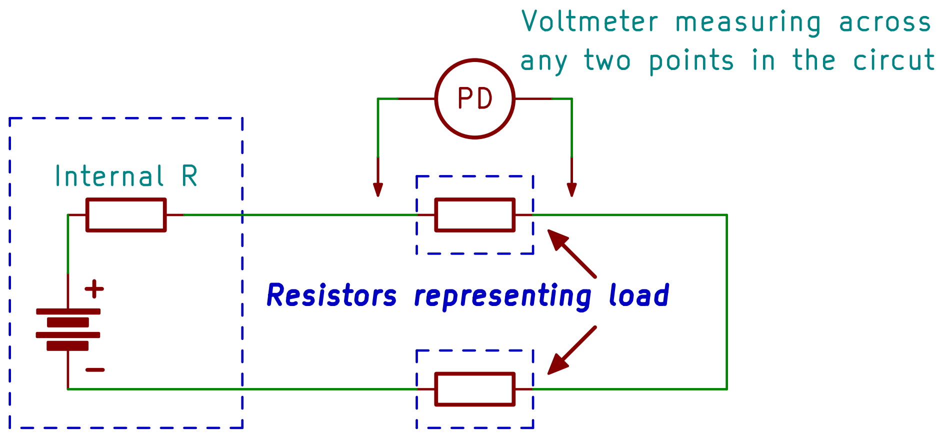

Figure 3-v: Measuring voltage (PD) between any two points in a closed circuit. [EI9ILB]

3.7 Voltage and Current in Series and Parallel Circuits

The way current and voltage are distributed in a circuit is described by Kirchhoff's current and voltage laws. The meaning of those laws can be simplified if we look separately at a simple series and a parallel connected circuit.

3.7.1 Series Connected Circuit

A SERIES CONNECTED CIRCUIT has components connected to each other so that the end (terminal) of one component is connected to the end of only one other component. Figure 3-vi shows three components: a voltage source, for example a battery, and two resistors. The positive terminal (end) of the battery is connected to the first resistor, which is connected to the second resistor, whose other terminal is connected to the battery's negative terminal. As you can see, each terminal of each component is connected to only one other component in a *series* connected circuit.

The *same current* flows through each component of a series connected circuit. In Figure 3-vi this can be expressed as:

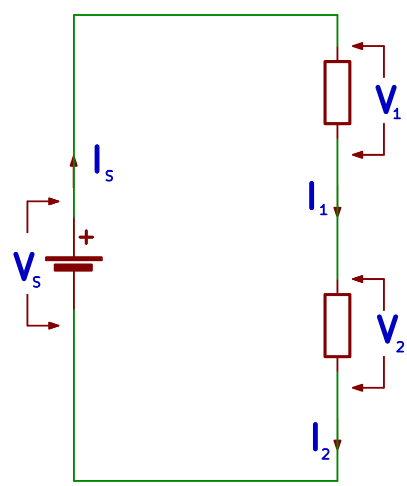

Figure 3-vi: Currents and Voltages in a Series Connected Circuit. [EI9ILB]

$$I_1 = I_2 = I_S$$

Each of the components of this circuit affects the voltage. The source creates it, and each resistor causes it to drop, as will be explained in section 3.9. However, the *source voltage* in a series circuit is equal to the *sum* of the individual voltages *across*

all the remaining components of that circuit. In other words, if you were to measure the voltage across every component in a series circuit, and add them together, the total figure would be the same as that of the source. In this figure, this can be expressed as:

$$V_1 + V_2 = V_S$$

3.7.2 Parallel Connected Circuit

In a PARALLEL CONNECTED CIRCUIT, a terminal of a component is connected to *more than one* other component. In Figure 3-vii you can see three components: a voltage source and two resistors. However, unlike in the Figure 3-vi, these components are connected differently. You can see that the positive terminal of the battery is now connected to two – not one – resistors. In other words, the upper terminal of each resistor is connected to the other resistor's terminal *and* to the battery's positive terminal. The negative terminal of the battery is connected to the other terminals of the resistors. In a *parallel* connected circuit, a terminal of a component is connected to *more than one* other device. This connection point is called a JUNCTION. You can see two junctions marked with a large green dot in Figure 3-vii. There are three BRANCHES, each starting and ending at the two junctions of this circuit.

All branches of a parallel connected circuit have the *same voltage*. This can be expressed, based on Figure 3-vii as:

$$V_1 = V_2 = V_S$$

The *current* flowing from the source's branch is equal to the *sum* of the remaining branch currents. This can be expressed as:

$$I_1 + I_2 = I_S$$

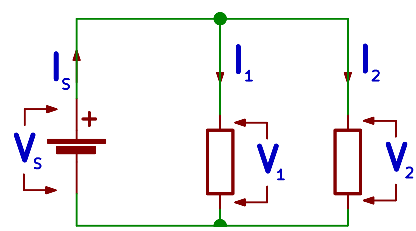

Figure 3-vii: Currents and Voltages in a Parallel Connected Circuit. [EI9ILB]

3.8 RESISTANCE

RESISTANCE is the opposition to the flow of the current. Although conductors allow current to flow through them, all conductors offer some opposition to its flow. They have some resistance. Different conductors oppose it by different amounts.

The letter R is the dimension symbol for resistance. The unit of resistance is the OHM, and its unit symbol is the Greek letter omega, Ω.

Current flowing through a conductor depends on the value of the conductor's resistance and on the voltage applied to it.

3.9 Ohm's Law

OHM'S LAW is fundamental to all electronics and electromagnetism. Understanding it will help you understand other aspects of radio theory. It states that the flow of the current depends on voltage and resistance. Specifically, it means that:

1 current is *directly* proportional to voltage, which means that the current *increases* when the voltage *increases,* as long as the resistance is not being changed, and,
2 current is *inversely* proportional to resistance, which means that the current *decreases* when the resistance *increases,* assuming that the voltage remains unchanged.

Ohm's law can be written in many ways, all of which mean the very same thing. Table 3-C shows a few common forms which you may see in the literature.[27] The first two, at the top of the left-hand column, are the most common. Bear in mind that both letters E and V may be used to mean voltage in these formulae. Each column in the table shows one of the three versions of the law. The column on the left shows how to calculate the voltage, the middle one shows how to derive the resistance, and the righthand column shows how to calculate the current.

$\boldsymbol{V = I \times R}$	$\boldsymbol{R = V / I}$	$\boldsymbol{I = V / R}$
$V = IR$	$R = \dfrac{V}{I}$	$I = \dfrac{V}{R}$

Table 3-C: Ohm's law formulae

3.9.1 Ohm's Law Example

Figure 3-viii shows a simple electrical circuit consisting of a 20 V battery and a 100 Ω resistor connected to each other. What is the current, in amperes, that is flowing through this circuit? Using Ohm's law:

$$I = \frac{V}{R} = 20\ \text{V} / 100\ \Omega = 0.2\ \text{A}$$

If V is 20 V and R is 100 Ω, then I is 0.2 A. This can be also expressed as 200 mA (milliamps) because 1 A is 1000 mA.

27 The HAREC syllabus requires candidates to be familiar with the formulae used in the syllabus and to be able to *transpose* them. Each of the formulae shown in the table are equivalent to each other because they have been derived by transposing, that is, rearranging one into another. This is done by simultaneously adding or subtracting, dividing or multiplying, both sides of the formula by the same variable, such as V, I, or R. Search the Internet for *Transposition of formulae* or *Changing the subject of an algebraic formula* for a refresher. Alternatively, memorise a few of variants of the formula.

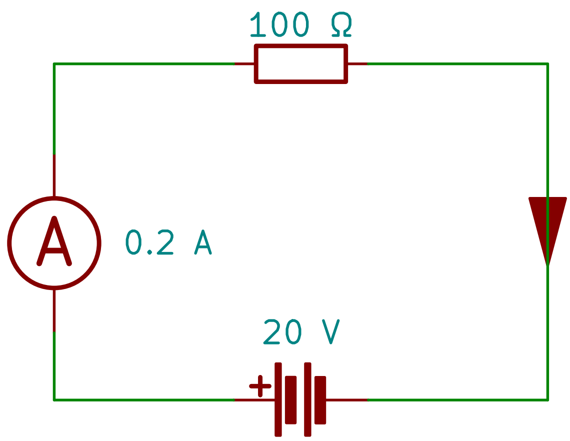

Figure 3-viii: Example circuit for applying Ohm's Law. [EI9ILB]

To get more practice, make up any other two values, then try finding the third one using Ohm's law. Circuits containing multiple resistors, which call for more complex uses of Ohm's law, are explained in Chapter 4 Resistors in Circuits.

3.10 Electric Power and Energy

3.10.1 Electric Power

In addition to voltage and current, there is another important physical quantity related to electricity: POWER. Understanding and being able to calculate power is very useful. For example, if the power requirements of the station are known, it is possible to calculate how long a battery may last before it is depleted. It helps to predict how powerful radio signals can be if the output power and the power handling characteristics of the antenna are known. Power is also important when considering safety.

POWER tells us how much WORK can be performed in a given amount of time.[28] Power also tells us how fast ENERGY is transferred or used in the circuit, i.e., the rate of the use of energy. The dimension symbol of power is the letter P. The unit of measurement of power is the WATT, and its unit symbol is W.

If both voltage and current are known, electric power can be easily calculated:

$$P = V \times I$$

which can be also written as:

$$P = VI$$

28 Standard work is defined in terms of the lifting of a weight against the pull of gravity. The heavier the weight or the higher it is lifted, and more work is done. Power is a measure of how rapidly a standard amount of work is done. In physics, there is no difference between work done by a mechanical force, or by the force of an electric or a magnetic field.

which means: P (power in watts) equals V (voltage in volts) multiplied by I (current in amps).[29]

3.10.2 Power and Ohm's Law

Ohm's law allows us to calculate the voltage, current, or resistance from any of the other two quantities. This is useful, because if you know the resistance, but you do not know the voltage or current you can still calculate the power. The next few formulae have been derived from the formula for power:

$$P = V \times I$$

and the formula of the Ohm's law:

$$V = I \times R$$

To obtain power P in watts from resistance R in ohms, if you know the current I in amps, but you do not know the voltage, use this formula:[30]

$$P = I^2 \times R$$

which can be also written as:

$$P = I^2 R$$

$$P = I \times I \times R$$

The following steps shows how the above formula was derived from Ohm's law. First of all, electric power is defined as:

$$P = VI$$

and Ohm's law states that:

$$V = IR$$

V in the formula for power can be substituted with IR from the right-hand side of the Ohm's law formula:

$$P = VI = (IR)\,I = I \times I \times R = I^2 R$$

29 Mathematical formulae normally omit the multiplication symbol. VI is equivalent to $V \times I$, where $\times$ denotes the multiplication operator.

30 Bear in mind that the number ^{2} appearing above letters I or V is not a footnote reference. It denotes a *square,* that is, multiplication of the quantity by itself. In other words: $I^2 = I \times I$ and $V^2 = V \times V$. This could be continued with numbers other than 2. Those are known as *powers of a number* – not *electrical power* but an operation of multiplying the quantity by itself as many times as the number shows. For example, $P^4 = P \times P \times P \times P$. It is a handy shortcut. Mathematical powers can also be negative, such as P^{-2} in which case they mean a *fraction* of 1 with the power of the quantity in the denominator: $d^{-2} = 1/d^2$. You will see this when learning about the *inverse square law,* which applies to radio signals. The power of a signal reduces as you move away from the antenna. Power drops by the square of the distance from the antenna.

Similarly, other equivalent variants of Ohm's law can be used in the formula for power to substitute I or R. For example, to calculate power in watts from resistance in ohms if you know the voltage in volts, but you do not know the current, we substitute I in the power formula with V / R:

$$P = VI = V\frac{V}{R} = \frac{V \times V}{R} = \frac{V^2}{R}$$

which can be also written as:

$$P = V^2/R$$

In a similar way, Ohm's law can be used to find out the resistance if you know the voltage or current and the power. For example:

$$R = V^2/P$$

which is equivalent to:

$$R = \frac{V^2}{P}$$

For example, using the simple circuit shown in Figure 3-viii on page 23, where a resistor of 100 Ω is connected to a source of 20 V, Ohm's law gives that the current is 0.2 A. You may now want to know what *power rating* to use for that resistor, because the power transferred in that circuit will have to be dissipated in it as heat, to prevent it from burning it out. You can calculate the power in several ways, depending on which of these quantities were known to you. For example:

$$P = VI$$

$$P = 20\ \mathrm{V} \times 0.2\ \mathrm{A} = 4\ \mathrm{W}$$

$$P = V^2/R$$

$$P = (20\ \mathrm{V})^2/100\ \Omega = 400\ \mathrm{V}^2/100\ \Omega\ = 4\ \mathrm{W}$$

Be careful about any metric prefixes when doing calculations in physics. It is possible to make these calculations with prefixes, but it is easier if you eliminate them. If there are *any* metric prefixes, such as *kilo, mega, milli* etc., first convert the values so that the prefixes go away by using Table 3-B: Selected SI metric prefixes on page 15 and the explanations shown below it.

For example, if you were asked about the same circuit as shown in Figure 3-viii but the values were expressed as 20 V and 200 mA you would first need to convert 200 mA (milliamps) to A (amps). According to Table 3-B, 1 m (milli) is 0.001, therefore:

$$200\ \mathrm{mA} \times 0.001 = 0.2\ \mathrm{A}$$

3.10.3 Electrical Energy and Battery Capacity

The measure of ELECTRICAL ENERGY indicates how much electric *power* can be provided or used in a period of *time* to perform some *work*. It is normally measured in units of kWh (kilowatt-hour) and its dimension symbol is W. It is calculated by multiplying the power P in watts by the time t in hours during which the electrical energy is supplied, transferred, or consumed:

$$W = P \times t$$

For example, to supply 1000 W of power for a period of 1 hour, you would need 1000 Wh (watt-hours) of energy, which is equivalent to 1 kWh, because the metric prefix k (kilo) means 1000. You may be already familiar with this concept because the electrical energy supplied to our homes is priced in cents per kWh.[31]

As already explained in 3.4 Sources of Electricity and Electromotive Force, batteries have a finite capacity of energy that they can store. It is possible to express their capacity in kWh, as is frequently done when describing electric vehicle (EV) batteries nowadays. However, there is another unit of battery capacity, ampere-hours, which is often seen on the smaller batteries that are used for portable radio operations.

Battery capacity measured in A·h (AMPERE-HOUR) describes how much current (amps) the battery can supply in an hour. For example, an 8 A·h battery can supply:

- 8 A for 1 hour
- 4 A for 2 hours
- 16 A for 30 minutes, and so on.

If the battery capacity, in A·h, and the *voltage* that it can supply are known, it is possible to convert its capacity to Wh (and kWh) using the power formula $P = VI$. For example, assuming the above 8 A·h battery supplies 12 V, the electric energy it could provide, in Wh, could be calculated this way:

$$8\ \mathrm{A \cdot h} \times 12\ \mathrm{V} = 96\ \mathrm{Wh}$$

and because 1 Wh = 0.001 kWh:

$$96\ \mathrm{Wh} = 0.096\ \mathrm{kWh}$$

Bear in mind that real-word batteries drop their voltage as they deplete, which makes the ampere-hour way of expressing their capacity quite realistic. This is one of the reasons why A·h is more popular for measuring smaller battery capacities.

31 At the time of writing, 1 kWh of electricity cost between €0.10–€0.50 in Ireland.

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4 Resistors in Circuits

THREE EXAM QUESTIONS · SECTION A4

4.1 Circuits

An electronic CIRCUIT consists of individual components, such as resistors, transistors, etc., connected by conductors, such as wires or printed circuit board (PCB) traces, through which electric current can flow.

Circuit diagrams use lines and graphic symbols to represent the components. Lines represent the conductors that connect components to each other. You have already seen a circuit diagram in Figure 3-viii: Example circuit for applying Ohm's Law.

4.2 Resistors

A RESISTOR is an electrical component that has two ends. The two ends are also known as TERMINALS. It offers resistance, or opposition, to the flow of the electrons (the current) and their "pressure" (the voltage). It can become warm, or even hot, when the current is flowing, because resistors perform their work by dissipating energy as heat.

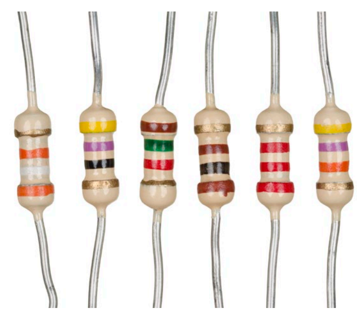

Figure 4-i: Resistors with different resistances
[Image by Evan-Amos, see page 375]

Resistors are designed to have a specific RESISTANCE, expressed in Ω (ohms) and a MAXIMUM POWER RATING in W (watts). Because of the variability of the manufacturing processes, resistors, like other electronic components, also have TOLERANCE, expressed as a percentage, for example, 1%, 5%, 10%, etc. Tolerance is sometimes written as ±1%, ±5%, ±10%. A nominal 100 Ω resistor that has a 10% tolerance can have an actual value of its resistance between 90 Ω and 110 Ω. The colour codes printed on a resistor specify the values of resistance, power rating, and tolerance. You do not need to know the colour codes of resistors and other component for the exam.

There are two sets of electronic symbols for resistors used on circuit diagrams, a zig-zag line, and a rectangle. The rectangle is the more recent one.[32]

32 The zig-zag line is an ANSI standard, mainly used in the USA, but also sometimes in Ireland and the UK. The rectangle is an IEC standard, currently used in Ireland, Europe, and the rest of the world. You need to know both symbols.

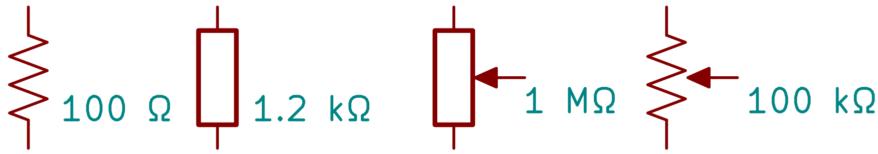

Figure 4-ii: Resistor symbols, from left to right: 100 Ω, 1.2 kΩ, 1 MΩ potentiometer, 100 kΩ potentiometer. [EI9ILB]

POTENTIOMETERS, or *pots,* shown on the right-hand side of Figure 4-ii, are a type of variable resistor.[33] By turning a knob, or moving a slider, they change their resistance. Many electronic devices have them, such as volume knobs etc.

Resistors, like other components, obey Ohm's law. That means that as the applied voltage increases, the current flowing through the resistor increases proportionately.

4.2.1 Resistor Power Rating

When current passes through a resistor, it dissipates power as heat. Resistors have a specified maximum POWER RATING, such as 0.25 W, 0.5 W, 1 W, 2 W, 5 W, etc. If this rating is exceeded, the component may burn out and fail!

Power rating for a resistor can be calculated using the formulae from section 3.10.2 Power and Ohm's Law. The resistance and either the voltage or the current need to be known. Recall that:

$$P = I^2 R$$

$$P = V^2/R$$

For example, a 5 kΩ (kilohm) resistor handling 10 mA (milliamps) will dissipate:

$$\begin{aligned} P &= (10 \times 0.001)^2 \times (5 \times 1000) \\ &= (0.01)^2 \times 5000 \\ &= (0.01 \times 0.01) \times 5000 \\ &= 0.0001 \times 5000 \\ &= 0.5 \text{ W} \end{aligned}$$

As another example, a 1 MΩ (megohm) resistor handling 1.5 kV (kilovolt) will dissipate:

$$\begin{aligned} P &= (1000 \times 1.5)^2 \,/\, (1 \times 1000000) \\ &= (1500)^2/1000000 \\ &= (1500 \times 1500) \,/\, 1000000 \\ &= 2250000 \,/\, 1000000\ \Omega \\ &= 2.25 \text{ W} \end{aligned}$$

In this case, a 1 MΩ resistor with a power rating of 5 W would meet and exceed the requirements, but one rated 2 W would not, and might burn out.

33 A potentiometer has *three* terminals so that it can be used as a voltage divider. There is also another type of a variable resistor, with only two terminals, known as a *rheostat.*

4.2.2 Resistors Connected in Series

To connect RESISTORS IN SERIES just one end (terminal) of a resistor is connected to the end of another resistor, leaving the other ends connected to something else, but not to each other.[34]

The EQUIVALENT RESISTANCE value of resistors connected in series, R_{eq}, is the *sum* of the resistances of all the connected resistors:

$$R_{eq} = R1 + R2 + R3 \ldots$$

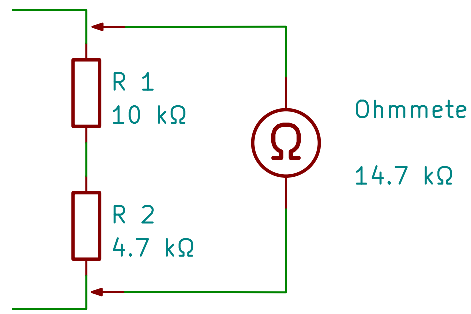

Figure 4-iii: Two resistors, 10 kΩ and 4.7 kΩ, connected in series. Equivalent resistance is 14.7 kΩ. [EI9ILB]

Resistors connected in series increase the overall equivalent resistance. It is always greater than the largest resistance of any of the resistors connected in series.

For example, as shown in Figure 4-iii:

$$R_{eq} = R1 + R2 = 10\ \text{k}\Omega + 4.7\ \text{k}\Omega = 14.7\ \text{k}\Omega$$

When metric prefixes of all resistances are the same, like k (kilo) in this case, it is not necessary to convert them to remove the prefix. You can add them as-is, and the result will carry the same prefix – kilo in this case – as the prefix that is shared by all the individual values. If the prefixes differ, it is necessary to convert them so that either the prefixes are removed altogether or made identical to each other. This was further explained under Table 3-B: Selected SI metric prefixes on page 15.

4.2.3 Resistors Connected in Parallel

To connect resistors IN PARALLEL, both terminals of a resistor are connected to both terminals of each other resistor.[35] Calculating their equivalent resistance is different from resistors connected in series.

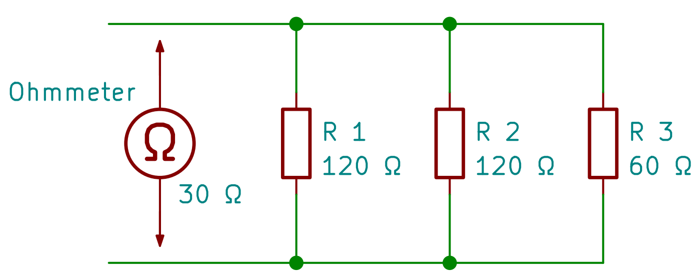

Figure 4-iv: Resistors in parallel: 120 Ω, 120 Ω, and 60 Ω. Equivalent resistance is 30 Ω. [EI9ILB]

34 See 3.7.1 Series Connected Circuit for a general explanation of these types of circuits.
35 See 3.7.2 Parallel Connected Circuit.

The equivalent resistance of resistors connected in parallel, R_{eq}, is the *inverse* of the *sum* of the *inversed* resistances.[36]

$$\frac{1}{R_{eq}} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} \dots$$

However, because the above formula's intermediate result is still inversed, we need to invert it to find out the R_{eq}:

$$R_{eq} = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} \dots}$$

Unlike resistors connected in series, resistors connected in parallel *reduce* the overall value in comparison to the resistances of the individual resistors. The equivalent resistance is always *less* than that of the smallest connected resistance.

For example, using the circuit in Figure 4-iv:

$$\begin{aligned} 1/R_{eq} &= 1/R1 + 1/R2 + 1/R3 \\ &= 1/120 + 1/120 + 1/60 \\ &= 4/120 \\ &= 1/30 = 0.0333 \dots \end{aligned}$$

Bear in mind, that $1/30$ (0.0333...) is not yet the final answer! We have only calculated $1/R_{eq}$. To find the equivalent resistance, we still need to invert that intermediate result. Therefore, the total equivalent resistance R_{eq} is:

$$R_{eq} = {}^{1}\!\big/_{\frac{1}{30}} = 30\ \Omega$$

You can calculate those numbers either by using a calculator,[37] remembering to invert the result, or manually, by adding the fractions, having found a common denominator first.

In the above example the resistances did not have any metric prefixes, they were stated in Ω. Just like when working with resistors in series, if there were different metric prefixes, it would be necessary to convert their values so that all the prefixes are the same, or to altogether remove the prefixes.

4.2.4 Multiple Resistors in a Circuit

Most circuits have multiple components with different resistances. Being able to calculate their overall equivalent resistance, no matter how connected, is not only necessary while working on those circuits, but it is also fundamental to other aspects

36 *Inverse* of a number means 1 *divided* by that number. For example, inverse of 2 is 1/2 which is ½ which is 0.5. Inverse of 10 would be 1/10 which is 0.1. Inverse of 0.5 is 1/0.5 which is 2. Inverse of 0.1 is 1/0.1 which is 10.

37 A simple calculator will be provided for the duration of the exam. It can add, subtract, multiply, and divide, however, it does not have more complex functions, such as squares or square roots. Please contact the IRTS Exam Board if you would like to know more about the provided calculators.

of electronics. It will help you understand how inductance, capacitance, and impedance function in real circuits. In turn, you will use this knowledge when constructing your station to ensure the best transfer of power between your transceiver and the antenna.

When a circuit has multiple resistors, and perhaps other components, like a battery, some will be connected in parallel and some in series. Follow these three steps to find their overall equivalent resistance.

1. First, calculate the equivalent resistance of the *parallel* connected resistances.
2. Then, calculate the *series* value to obtain the overall equivalent resistance.
3. Finally, use Ohm's law to calculate the current, voltage, and power.

4.2.5 Worked Example: Current, Voltage, and Power with Multiple Resistors

The next example shows how to combine all the knowledge presented so far, especially the Ohm's law, as applied to current, voltage, and resistance, and as it is applied to calculating power dissipated by the resistors.

For a complete understanding of this example, you should also have a grasp of how currents flow, and how voltages appear across a circuit that contains branches, i.e., a circuit containing both series and parallel connected components. Please review section 3.7 Voltage and Current in Series and Parallel Circuits if needed.

This is a more complex and more time-consuming exercise than the examples presented so far. Being able to do calculate all the currents, voltages, resistances, and powers, across the circuit confirms that you have a good understanding of Ohm's law and of the related principles.

4.2.5.1 *Question*

Given the voltage of the battery, and the values of the three resistors, calculate voltages, currents, and powers in all parts of the circuit shown in Figure 4-v.

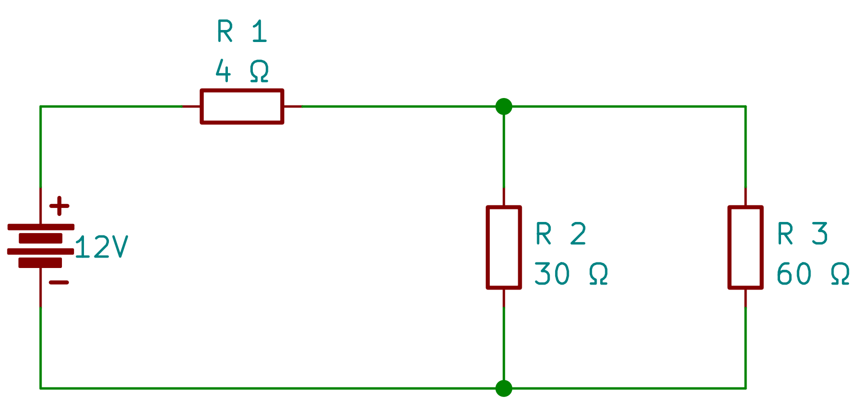

Figure 4-v: Circuit with a 12 V battery connected in series to a 4 Ω resistor, which is connected to two resistors, 30 Ω and 60 Ω which are connected in parallel to each other. [EI9ILB]

4.2.5.2 *First Steps: Total Equivalent Resistance, Current, and Power*

We begin by calculating the equivalent resistance of the parallel resistors $R2$ and $R3$. Both methods are shown here: first using fractions, which requires finding a common denominator of $1/30$ and $1/60$, and then by using a calculator, which requires some rounding of long numbers.

1 Add inverted resistances to obtain the intermediate result:

$$\frac{1}{30}+\frac{1}{60}=\frac{2}{60}+\frac{1}{60}=\frac{3}{60}=\frac{1}{20}$$

$$1/30 + 1/60 = 0.033 + 0.017 = 0.05$$

2 Invert the intermediate result to get the equivalent parallel resistance:

$$1 \Big/ \tfrac{1}{20} = 20\ \Omega$$

$$1/0.05 = 20\ \Omega$$

Next, we add the equivalent series resistance of the 4 Ω resistor $R1$ and the just calculated equivalent resistance of the parallel combination of $R2$ and $R3$, which was found to be 20 Ω:

$$4\ \Omega + 20\ \Omega = 24\ \Omega$$

Using Ohm's law, we can calculate the total current in the circuit:

$$12\ \text{V} \ /\ 24\ \Omega = 0.5\ \text{A} = 500\ \text{mA} = 0.5\ \text{A}$$

With the known total current, we can use the formula for power, $P = VI$, to calculate the power dissipated by the entire circuit:

$$P = VI = 12\ \text{V} \times\ 0.5\ \text{A} = 6\ \text{W}$$

Alternatively, we could have calculated the total power using the formula of voltage and resistance, $P = V^2/R$:

$$P =\ V^2/R = \frac{V^2}{R} = \frac{12^2}{24} = \frac{144}{24} = 6\ \text{W}$$

Yet another way to get the same total power would use the formula of current and resistance, $P = I^2R$:

$$P = I^2R = 0.5^2 \times 24 = 0.25 \times 24 = 6\ \text{W}$$

Which formula should you use depends on what information is available to you and what is unknown.

The current divides between the parallel resistors, as shown in Figure 4-vi. You can use Ohm's law to calculate all the remaining currents, voltages, and powers, in

all parts of the circuit. As an exercise, see if you can figure out the necessary calculation steps to match all the results shown below. The answers are shown in Figure 4-vi, and the necessary steps are listed in the next subsection.

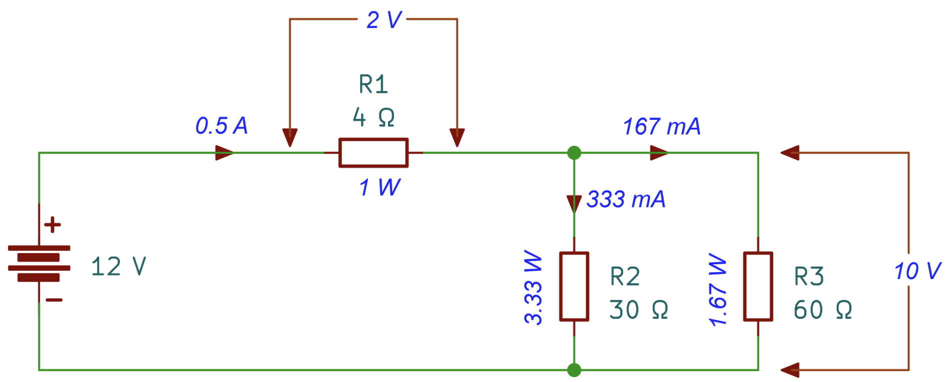

Figure 4-vi: Worked example showing voltages, currents, and power of the same circuit as shown in the previous figure. The total power used by this circuit is 6 W. [EI9ILB]

4.2.5.3 *Steps to Find the Remaining Voltages, Currents, and Powers*

There are different ways how the remaining voltages, currents, and powers can be calculated. The steps below are just a suggestion.

Find out the voltage across $R1$ using the just calculated total circuit current, 0.5 A, and Ohm's Law, $V = IR$

$$V1 \ = IR1 = 0.5\,\mathrm{A} \times 4\,\Omega = 2\,\mathrm{V}$$

Use Ohm's law power formula to calculate power $P1$ dissipated by $R1$

$$P1 = V1\,I = 2\,\mathrm{V} \times 0.5\,\mathrm{A} = 1\,\mathrm{W}$$

Since $R2$ and $R3$ are connected in parallel, their voltages $V2$ and $V3$ must be the same, $V2 = V3$. See 3.7.2 Parallel Connected Circuit for a reminder why this is the case.

The source voltage, V, supplied by the battery is equal to the *sum* of voltage $V1$ for resistor $R1$ and voltage $V2$. This is because the source voltage in a circuit comprised of components connected is series is equal to the sum of the voltages across those components, see 3.7.1 Series Connected Circuit

$$V1 + V2 = V$$

We can rearrange this to calculate $V2$

$$V2 \ = V - V1 = 12 - 2 = 10\,\mathrm{V}$$

An alternative way to calculate $V2$ would use Ohm's law directly by treating the two parallel connected resistors $R2$ and $R3$ as one unit, lumped together. We already

know that their combined resistance is 20 Ω. We also know that the current flowing into and out of that part of the circuit is 0.5 A.

Therefore:

$$V = IR = 0.5\text{ A} \times 20\ \Omega = 10\text{ V}$$

We can now proceed to calculate the currents $I2$ and $I3$ flowing through resistors $R2$ and $R3$. Using Ohm's law:

$$I = \frac{V}{R}$$

$$I2 = \frac{V2}{R2} = \frac{10\text{ V}}{30\ \Omega} = 0.333\text{ A} = 333\text{ mA}$$

$$I3 = \frac{V3}{R3} = \frac{10\text{ V}}{60\ \Omega} = 0.167\text{ A} = 167\text{ mA}$$

The results above have been rounded to show only three digits after the decimal point.[38]

We can confirm that our results are correct by making a few observations. As explained in 3.7.2 Parallel Connected Circuit, the current flowing from the source's branch is equal to the sum of the remaining branch currents. We can confirm that by adding $I2$ to $I3$:

$$I = I2 + I3 = 0.333\text{ A} + 0.167\text{ A} = 0.5\text{ A}$$

We already know that the voltages across $R2$ and $R3$ are equal. We can observe that twice as big resistance of $R3$ than $R2$ causes the current through $R3$ to be half of the current flowing through $R3$.

Finally, we can calculate the powers dissipated by $R2$ and $R3$ using any of the three power formulae, since we know the current, the voltage, and the resistance.

For example, using the simplest formula, $P = VI$, we find out $P2$ and $P3$:

$$P2 = V2\,I2 = 10\text{ V} \times 0.333\text{ A} = 3.33\text{ W}$$

$$P3 = V3\,I3 = 10\text{ V} \times 0.167\text{ A} = 1.67\text{ W}$$

We can verify our result by observing that the power dissipated by $R3$ is half the power dissipated by $R2$, and that the total power dissipated by the circuit, 6 W, is the sum of the powers dissipated by all the three components, $R1$, $R2$, and $R3$:

$$P = P1 + P2 + P3 = 1\text{ W} + 3.33\text{ W} + 1.67\text{ W} = 6\text{ W}$$

38 Numbers are usually rounded by removing unwanted digits and leaving the wanted ones, subject to a small modification to the last remaining digit. The remaining digit is increased by 1 if the removed digit that followed it was 5–9, otherwise it is left unmodified. That is why 0.333333... is rounded to 0.333, but 0.166666... is rounded to 0.167.

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5 Alternating Current and Sinusoidal Signals

FOUR EXAM QUESTIONS · SECTION A3

Unlike DC, which always flows in the same direction, AC changes its direction many times per second. There are other important differences. DC usually keeps the current and voltage somewhat constant, unless something happens, like a switch is turned on or off, or the battery starts discharging. AC, on the other hand, changes its voltage, and current, all the time. If those changes were random or chaotic, such a type of AC would not be of interest to us. However, the AC that we use in radio behaves in a well organised, perhaps even beautiful manner.

The most important type of AC, especially to radio and electromagnetism, is one in which the changes of the direction, current, and voltage follow the pattern of a sine. This chapter explains the sine pattern in detail.

5.1 Sinusoidal Signals

The example shown in Figure 5-i shows a graph of a line known as a SINE. Another name for a sine is a SINUSOID, from which comes the term *sinusoidal*. In radio terms, this graph represents a SINUSOIDAL SIGNAL, also known as a SINE WAVE, or a PURE SINE WAVE.

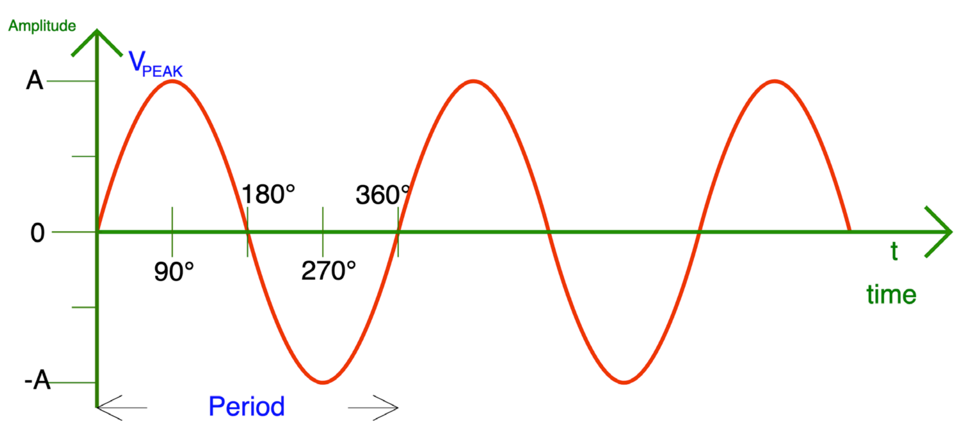

Figure 5-i: Sinusoidal signal and its period, time on the horizontal axis. [EI9ILB]

This signal's strength, or amplitude, varies over time. Time is usually represented on the horizontal axis, also known as the *x* axis. Plots like this one, which show the time on the *horizontal* axis, are also known as plots in the TIME DOMAIN.

When reading these plots, you can think of the passage of time in absolute or relative terms. Absolute terms would show actual seconds, minutes etc. on the *x* axis. In

this case, however, we are looking at relative rather than absolute terms. Time is expressed in periods of an arbitrary duration.

One period is the time that the signal takes to complete a full cycle. The vertical, or the *y* axis, shows the amplitude (strength) of the signal in terms of its voltage. In this case, it goes as high as some high value of volts, denoted by A, and as low as −A volts[39]. One cycle of a signal takes it, in this case, from having amplitude of zero, that is no signal at all, through a peak of A, then back to zero, then to −A, before going back to zero.

Bear in mind that −A is an amplitude of AC that is flowing in the opposite direction, but with the same voltage, as A. The only difference between the negative and positive amplitude value is the direction in which the current flows.

Sinusoidal signals are cyclical: as the time passes, each cycle represents a revolution of a circle. That is why you see angles, in degrees, on this graph: start at 0°, reaching the peak amplitude at 90°, back to zero at 180°, reaching the peak negative amplitude at 270°, and back to zero at 360° where the cycle completes and the next one starts.[40]

To describe any sinusoidal wave (signal) you need to know its: amplitude and its period or its frequency. From those, you can calculate all other values because the sinusoidal pattern always has the same shape. Those other values that are useful to know include: instantaneous value, average value, effective or rms voltage, and power. They are explained in the rest of this chapter.

5.1.1 Amplitude

The AMPLITUDE or V_{PEAK} also known as V_{PK} and as V_{MAX} is the maximum voltage in either direction of the flow of the AC. It is expressed in volts (V). The positive value on top of the vertical axis indicates the peak voltage V_{PK} or V_{MAX} when the current flows in one direction. The same but negative value or V_{MIN} represents the voltage when the current is flowing in the opposite direction.

39 Letter A stands here for amplitude, not amps. This may be a little confusing, because, in this case, the amplitude of the signal is measured in volts (V) and not amps (A). The same letter can have different meanings depending on the context.

40 Mathematically, it is just a plot of the *sin* (sine, sinus) function, with the angle of a circle on the horizontal, or x axis, while the vertical, or y axis, would reach 1 at point A at the top, and -1 at point -A at the bottom. Since a circle has 360° (degrees), which are shown in this figure, you can see how the sine function starts at the value of 0 at 0°, reaches the peak of 1 at 90°, goes back to 0 at 180°, the trough of -1 at 270°, and back to 0 at 360° where the cycle begins again. In other words, $sin(0) = 0$, $sin(90°) = 1$, $sin(180°) = 0$ and so on. If you are geometrically minded, you may also want to think of those angles, here expressed in *degrees,* as angles expressed in sections of the circumference of a unit circle, which is 2π (π, or pi=3.14...). In this way of expressing angles, known as radians (named after the radius of a circle), you could write that $\sin(0) = 0, \sin(\pi/2) = 1, \sin(\pi) = 0$. While knowing this is not necessary for the exam, it may help you understand why formulae for reactance and resonance refer to 2π. 2π is a full cycle in radians, that is, a full 360° of a wave, or simply its single full oscillation, like a full turn of a circle. See also footnote 48 on page 44.

5.1.2 Period and Frequency

The duration of one cycle is known as the PERIOD of the signal. It is measured in seconds (s). Signals, which have an identifiable period, are known as PERIODIC SIGNALS. All sinusoidal signals are periodic.

Because the signals that we use tend to have very short periods, it is more convenient to think of how many periods there are in one second. This very important number is known as the FREQUENCY. Its dimension symbol is f and its unit is HERTZ, whose unit symbol is Hz. 1 Hz is a signal whose period is exactly 1 second. There is exactly one cycle of the sinusoidal wave in 1 s if its frequency is 1 Hz.

If you know the frequency, you can easily calculate the period, and the other way round:

$$period = \frac{1}{f}$$

$$f = \frac{1}{period}$$

5.1.3 Wavelength and Frequency

The WAVELENGTH of a wave, or of a sinusoidal signal, is the *distance,* in metres (m), that the signal would propagate in *one period*. It is the distance that a point chosen on the wave, such as its beginning or a crest, would travel in the duration of one *period*. In other words, it is the distance between two successive crests of the wave.[41] It is the same as the distance between the 0° and the 360° points of the wave if you could see it and measure with a ruler.[42]

Figure 5-ii shows a plot of a sinusoidal signal's amplitude over the distance that it travels. You can read this plot in a similar way to how you read the *time domain* plot shown in Figure 5-i. You may notice that the two plots seem identical, except for a couple of labels. Instead of the passage of time, the horizontal axis now shows the distance the signal has travelled, starting at its source on the left, and moving away from it towards the right.[43] Also, instead of showing the *period* of the signal, which

41 It is the distance between two positive peaks, i.e., those at the top of the curve, also known as *crests,* or two negative troughs, i.e., those at the bottom, but *not* the distance travelled from the positive to the negative peak (crest to a trough). This can be a little confusing, because, as explained later, there is also a concept of the peak-to-peak voltage, which is measured between a positive and the negative peak (crest to trough). However, when measuring *wavelengths* or *periods* of a wave you have to choose two identical points on the wave, such as the two peaks at the top. More precisely, two points need to be chosen on the sinusoid that have the same *angular* distance from its start, measured in degrees, 0–360°, or in radians, 0–2π. Crests are at 90° (½ π) and troughs are at 270° (1½ π) for a sinusoid whose amplitude is zero at its start at 0°.

42 If you think of electromagnetic waves as *photons*, the wavelength would be the distance a photon would travel in one period of the wavelength. In vacuum, photons travel at the speed of light.

43 This plot is not a time domain plot, because the horizontal axis does not show time. It is known as a *spatial domain* plot because its horizontal axis shows the distance, which is a measure of physical space. Later in this guide you will also learn about the third type of plots: frequency domain. See section 6.2.1 Time and Frequency Domains.

was a measure of time, the plot below shows the wavelength, which like the distance, is a measure of length.

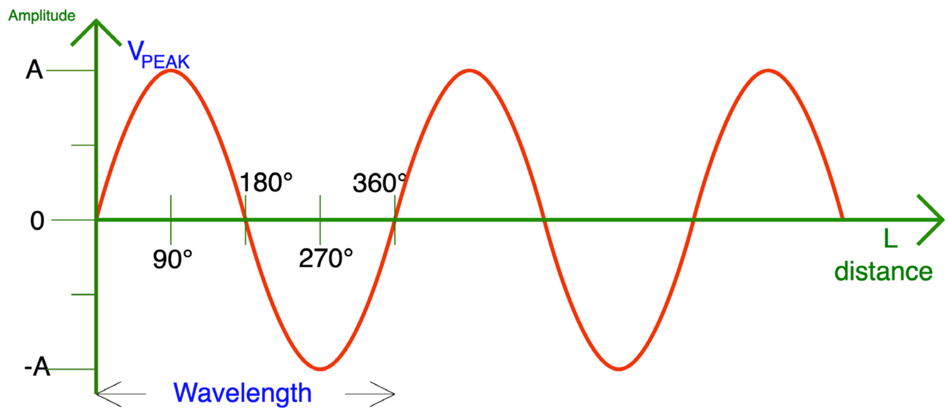

Figure 5-ii: Sinusoidal signal and its wavelength, distance on the horizontal axis. [EI9ILB]

If you know the frequency, or the period, of a signal, and the propagation speed, you can calculate its wavelength. The dimension symbol of wavelength is λ (Greek letter lambda) and its unit is a metre (m). It is just like anything else you would measure in metres.

In vacuum, radio waves propagate at the SPEED OF LIGHT, known as c and approximately equal to 300 000 000 m/s, which is 300 million metres per second.[44] They propagate *almost* at the speed of light in the air, and a bit slower in other materials, such as coaxial cables – that will be introduced in section 14.3 Velocity Factor.

If you know the period, i.e., how long it takes for the signal to complete a single cycle, then you can calculate the wavelength by simply multiplying the period (in seconds) by the speed of light (in m/s). The result will be in metres.

We often need to convert between frequency and wavelength of a signal. These important formulae are very similar to each other. Even an approximate conversion is helpful, for example, to know which frequencies correspond to which radio bands. To find out the wavelength λ you divide the speed of light c by the frequency f

$$\lambda = \frac{c}{f}$$

Recall that the metric prefix for a million is M (mega). Radio frequency f is often expressed in MHz (megahertz). The speed of light c can be expressed as 300 Mm (megametres). Because the metric prefixes are now the same, the formula for converting wavelength to frequency is very simple – as long as f is in MHz:

$$\lambda = \frac{300}{f}$$

44 The speed of light is 299 792 458 m/s, but we round it up to 300 000 000 m/s.

To find out the frequency in MHz from the wavelength in metres it is almost the same formula:

$$f = \frac{300}{\lambda}$$

For example, what is the wavelength λ of the 50 MHz frequency?

$$\lambda = \frac{300}{50\text{ MHz}} = 6\text{ m}$$

What is the frequency f of the 30 m wavelength?

$$f = \frac{300}{30\text{ m}} = 10\text{ MHz}$$

If you see frequency in anything other than MHz, make sure to convert it to MHz before using the above formula. Remember:

$$1000\text{ kHz} = 1\text{ MHz}$$

$$1\text{ kHz} = 0.001\text{ MHz}$$

5.1.4 Instantaneous and Average Values

The INSTANTANEOUS VALUE is the value of the sinusoid at any chosen point in time. It can be read out from the graph. For example, using Figure 5-i, the instantaneous value in the middle of the cycle is zero. It is $V_{PK} = V_{MAX}$ at ¼ of the cycle and it is $V_{MIN} = -V_{PK}$ at ¾ of the cycle. The AVERAGE VALUE of each *half-cycle* of a sinusoidal signal is:[45]

$$V_{AVG} = 0.636 \times V_{PK}$$

Be careful not to confuse the average value of a half-cycle with the rms value that is explained in the following section.

5.1.5 rms, Effective Voltage, Peak-to-Peak Voltage, Power

A sinusoidal signal oscillates between V_{MAX} and V_{MIN} all the time. Its instantaneous voltage changes all the time. This presents a problem if one needs a single figure of voltage for a calculation. For example, to calculate the power dissipated in a resistor, do we need to calculate it for *every* value between V_{MAX} and V_{MIN}? That is not necessary.

There is a very helpful way to express the EFFECTIVE VOLTAGE of any sinusoidal signal. This is also the voltage that is normally indicated by an AC voltmeter. It is known as the **rms** value. The abbreviation rms or V_{RMS} stands for *root mean square.*[46]

45 The average value of a *whole* cycle of a sinusoidal signal is always zero.

46 You may notice that the square root of 2, that is $\sqrt{2} = 1.4142136\ldots$ appears in the formula that relates V_{MAX} to V_{RMS}.

Bearing in mind that V_{PK} is another name for V_{MAX}, there are several ways to convert between V_{RMS} and V_{PK} for sinusoidal signals:

$$V_{RMS} = 0.707 \times V_{PK}$$

$$V_{PK} = V_{RMS} \,/\, 0.707 = 1.414 \times V_{RMS}$$

PEAK-TO-PEAK voltage V_{PP} is the voltage between V_{MAX} and V_{MIN}. It can be calculated from V_{RMS}

$$V_{PP} = 2.828 \times V_{RMS}$$

Figure 5-iii illustrates the relationship between peak, rms, and peak-to-peak voltages of a sinusoidal signal.

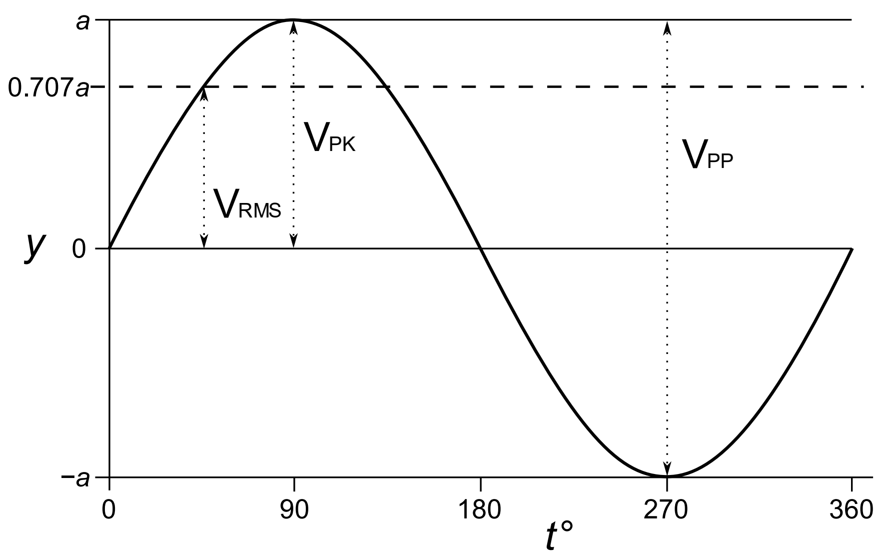

Figure 5-iii: Relationship between V_{RMS}, V_{PK} (V_{PEAK}, V_{MAX}) and V_{PP}
[Image by AlanM1, see page 375]

The key benefit of V_{RMS} is that it makes other AC calculations as easy as for DC, including Ohm's law and power formulas. For example, to find out the power dissipated as heat in a resistor used in an AC circuit, we can use the earlier DC formula by substituting V_{RMS} in place of V:

$$P = \frac{{V_{RMS}}^2}{R}$$

A resistor of 500 Ω in mains supply AC that has V_{RMS} of 230 V would dissipate:

$$P = \frac{(230\ \mathrm{V_{RMS}})^2}{500\ \Omega} = 105.8\ \mathrm{W}$$

5.2 Alternating Current

Normally, AC is a sinusoidal signal. The most common example of alternating current is the mains supply in every home. The characteristics of Irish mains supply are:

- rms voltage is 230 V_{RMS}
- peak voltage $V_{PK} = 1.414 \times 230\ \text{V} = 325\ \text{V}$
- peak-to-peak voltage $V_{PP} = 2.828 \times 230\ \text{V} = 650\ \text{V}$
- frequency[47] $f = 50\,\text{Hz}$
- period is $1\ \text{s}/50 = 0.02\ \text{s} = 20\ \text{ms}$ (milliseconds).

5.3 Phase

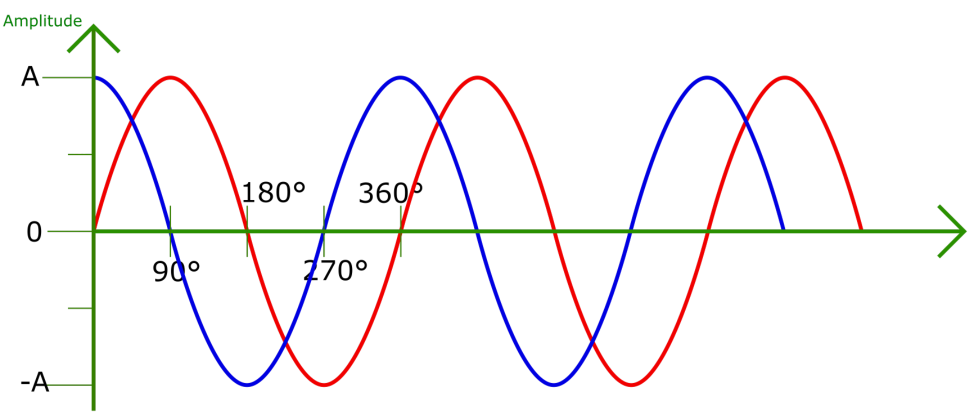

Figure 5-iv: Phase difference of sinusoidal signals. [EI9ILB]

If two signals have the same frequency but cross the zero line at different times, they have a PHASE DIFFERENCE. The blue wave in the figure above crosses the zero line ninety degrees before the red one. Blue LEADS the red by 90° or ¼ cycle.[48] The red LAGS the blue by 90° (one cycle is 360°).

Understanding phase differences will help you match your antenna and the transmission line to your transceiver. It will also help you understand how resonant circuits and components work, including capacitors and inductors.

47 Ireland, UK, the rest of Europe, and much of the world, use the same mains supply frequency of 50 Hz. Some countries, notably the USA, use 60 Hz.

48 As already mentioned in footnote 40 on page 39, instead of using *degrees* to describe phases (stages) of a sinusoidal cycle we can also represent them as fractions of a circle's circumference. That method of expressing angles is known as *radians*. For example, the angle of 90° represents the first ¼ of a cycle of the red sinusoid shown above in Figure 5-iv. The circumference of a unit circle, i.e., a circle whose radius is 1, is about 6.28, or 2π. π is an important number in all of mathematics. It can be rounded to 3.14 for the purposes of this guide, however, you do not need to know its actual value just to express angles of a circle. Instead, 90° or ¼ of a circle is ½ π or $\pi/2$, 180° or half of a circle is π, 270° or ¾ of a circle is 1½ π or $3/2\,\pi$, and finally, 360°, or the full circle, is 2π. Therefore, it could be said that the blue signal leads the red by ½ π.

5.4 Harmonics

A wave whose frequency is an exact *multiple* of another is called a HARMONIC. For example, a SECOND HARMONIC, shown in blue in Figure 5-v has a frequency that is *twice* that of the original signal. The original wave, shown in red, is also known as the FUNDAMENTAL FREQUENCY or as the FIRST HARMONIC.

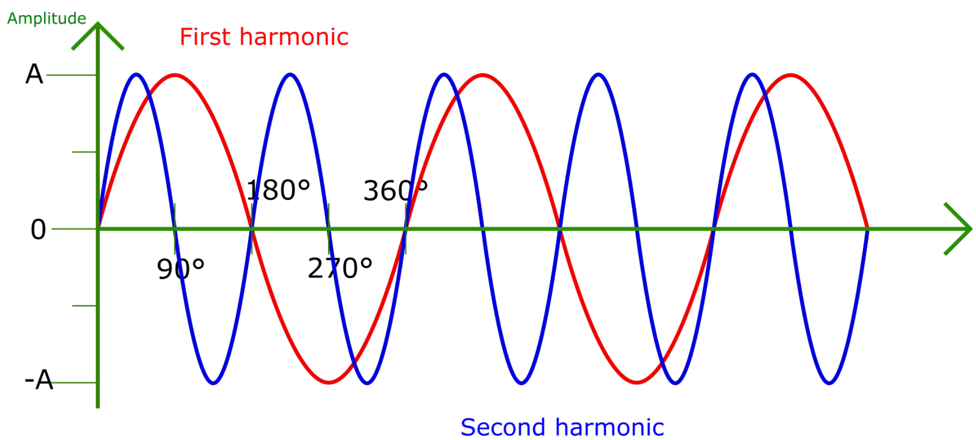

Figure 5-v: Second harmonic of a fundamental signal (first harmonic). [EI9ILB]

Understanding harmonics is important when evaluating transmitter quality. Poor transmitters generate unwanted harmonic signals. It causes interference and, if excessive, may even cause you to transmit outside of the allowed bands, breaking the law. Harmonics are also relevant to how resonant circuits work, including filters.

5.5 Modulated Sinusoidal Signals

How to transmit information is a perennial question of utmost importance in radio communication. A pure sine wave, such as the one shown in Figure 5-i: Sinusoidal signal, would carry no information, other than perhaps a constant, single note, like a never-ending beep.[49] On its own, a pure sine wave could merely inform someone that there is a transmission in place, but it would not be possible to convey any useful information that way, not even an identification of the transmitting station.

A pure sinusoidal signal, without any information in it, can be used as a carrier wave. It is its frequency, the carrier frequency, that you select using the tuning knob on your radio.

To transmit something interesting, such as speech, that information needs to be impressed upon the carrier frequency. This process is known as modulation. It will

49 You will occasionally hear that on the air, when someone is *tuning* their transmission system, and they are briefly transmitting a single tone to optimise their settings, perhaps by triggering an ATU, see 14.10 Antenna Tuning Units. A pure carrier wave, which is a sinusoidal wave without any information carried by it, can be used for that purpose. It would be normally followed by another transmission that contains useful information, including the call sign of the station.

be explained in detail in Chapter 11 Modulation and Modes. For now, think of it as a process of combining other sinusoidal and non-sinusoidal signals, which represent useful information, like voice or data, with the pure sine wave representing the carrier. The result of that process would be a modulated signal wave, which retains most of its original sinusoidal nature, such as the fundamental frequency, but which is no longer pure because it carries information that was impressed on it.

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6 Digital Signal Processing and Non-Sinusoidal Signals

SEVEN EXAM QUESTIONS · SECTIONS A3 A4

This chapter introduces non-sinusoidal signals. They represent two main types of information that we transmit using radio: *voice* and *digital data*. You will learn how those signals can be manipulated using Digital Signal Processing. You will also learn the fundamentals of Software Defined Radio.

6.1 Non-Sinusoidal Signals

There are many types of signals that are not sinusoidal. Some of them can cause problems, but the majority are very useful. Some of them can be regular in their shape, repeating the same pattern over and over. They are known as PERIODIC non-sinusoidal signals because even though they are not a sinusoid, they have a fixed, known amplitude, period, wavelength, and a frequency.

Other non-sinusoidal signals are NON-PERIODIC, also known as irregular, or aperiodic, and their shape changes all the time, depending on the information they are conveying. Most of the signals that we use in radio are non-periodic.

The information that we transmit is normally non-sinusoidal and non-periodic in nature. To transmit it, we modulate a sinusoidal carrier wave using such non-sinusoidal, non-periodic signals. The modulated signal wave combines periodic and non-periodic waves. Modulation will be explained in Chapter 11 Modulation and Modes. Non-sinusoidal signals can be also enhanced and manipulated using Digital Signal Processing (DSP), which is discussed in the next section.

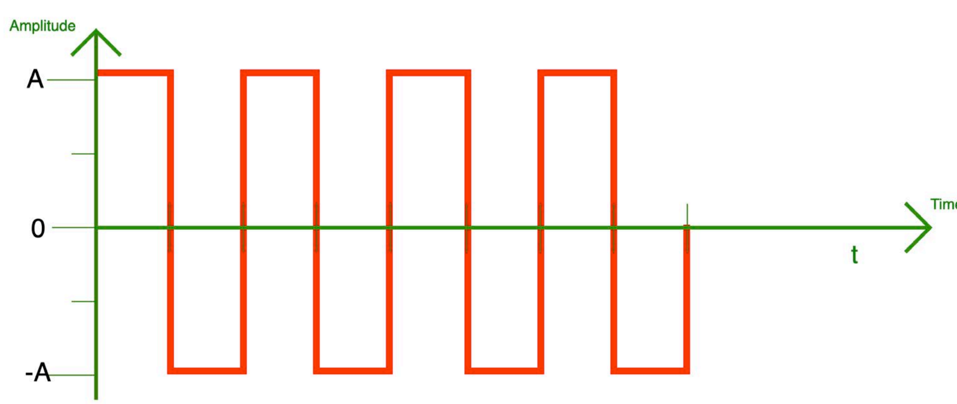

Figure 6-i: Square wave. [EI9ILB]

The example in Figure 6-i shows a SQUARE WAVE.[50] It is clearly *non-sinusoidal:* there are sudden transitions from the high peaks to their opposites, unlike in a sine wave, in which everything happens smoothly. However, it is *periodic:* the same pattern repeats with a perfect regularity.

You can read plots of non-sinusoidal signals in the same way as plots of sinusoids that were explained in section 5.1. The horizontal axis, also known as the x axis, shows the passage of time, from left to right. The vertical, or y axis, shows the amplitude of the signal that was observed at the moments in time represented by the horizontal axis. These types of plots are known as plots of signals in the TIME DOMAIN because the horizontal axis, which also known as the *domain,* shows *time.*

In nature, there are many other non-sinusoidal signals that are periodic, other than the square wave.[51]

Some digital signals, including Morse Code, look similar to a square wave. The figure below shows an example of a more complex digital signal, whose amplitude takes multiple values of interest.

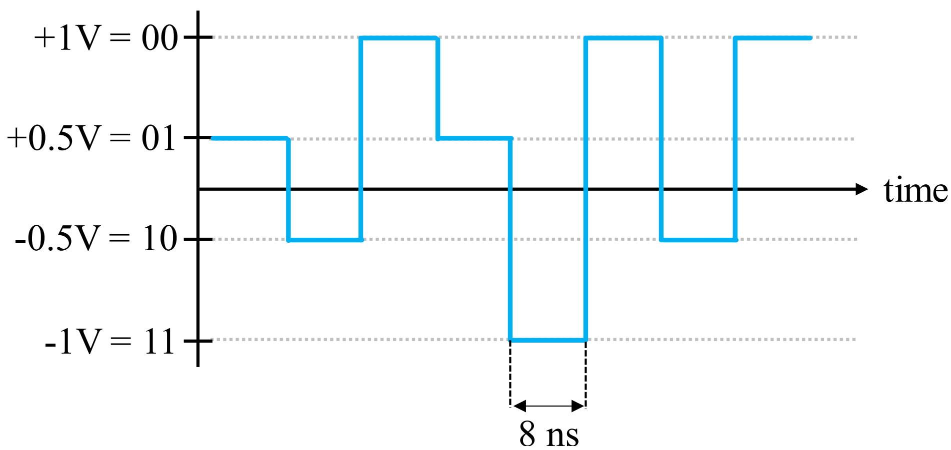

Figure 6-ii: Non-sinusoidal signal representing digital data (Ethernet).
[Image by Marc Lichtman KC3JTT, see page 375]

Square waves, if not properly treated, could also become a problem. Any instantaneous, or just very sudden, change of the amplitude causes the formation of many unwanted waves on harmonic frequencies.[52] If you fed a square wave signal directly to your antenna it would cause significant interference with other users of the radio spectrum. In more extreme cases, for example if such a signal were to be amplified,

50 A *square wave* can be also thought of as an infinite series of odd harmonics (3rd, 5th, 7th) of decreasing amplitude. See en.wikipedia.org/wiki/Square_wave

51 For example, a triangular wave or a sawtooth wave. They have some uses in radio and audio processing, See en.wikipedia.org/wiki/Triangle_wave and en.wikipedia.org/wiki/Sawtooth_wave

52 This is one of the reasons why *key clicks* are generated when Morse code is sent using a key or keyer that does not allow for a gentle *rise* and *fall* of the signal's amplitude. They are a nuisance to nearby frequencies and can cause significant interference on harmonically related bands.

it could damage your equipment because of the concentrated, large energies carried by square waves through equipment designed for gentler, more sinusoidal signals.

Such non-sinusoidal signals require additional processing, such as modulation, or the use of other components, or digital signal processing, to make them smoother or more sinusoidal before being transmitted. The figure below shows an example how a non-sinusoidal, square wave digital signal could be transformed, using modulation, into a combination of sinusoidal signals. This will be discussed in more detail in Chapter 11 Modulation and Modes.

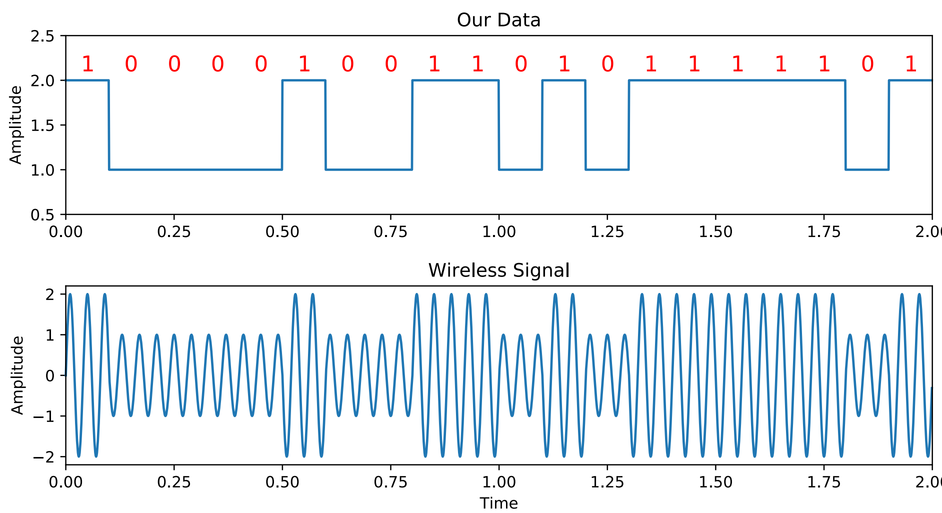

Figure 6-iii: Modulation of a non-sinusoidal digital signal to obtain a combination of sinusoids using amplitude shift keying (ASK).
[Image by Marc Lichtman KC3JTT, see page 375]

Audio speech is an interesting example of a non-sinusoidal, non-periodic signal. See Figure 6-iv for an example of a speech waveform. However, even though it is non-sinusoidal, it can be easily modulated and transmitted by radio. And, like all signals,[53] it can be also transformed into a combination of great many sinusoids of different frequencies, making its digital processing straightforward.[54]

Perfect human hearing detects audio in the range of 20 Hz–20 kHz. Human voice never ranges that far.[55] Frequencies in the range of 300 Hz–2.7 kHz make the most significant contribution to intelligibility of speech. That considerably narrow range

53 To be precise: like all *continuous* signals and on the assumption of a limit to the highest frequency of interest. In practice, all signals that we use have these two properties. An example of an exception that you would not encounter in practice would be signals comprised of infinitely narrow pulses.

54 Speech is an interesting composite waveform because some of its major components can be sinusoidal. Steady tones of voice, such as the steady note you hear when someone pronounces an elongated letter E or S are comprised of a relatively small number of sine waves and their harmonics.

55 Highly trained vocalists, such as operatic singers, can range 50 Hz–8 kHz. Upper frequency limit of human hearing drops as we get older. Adults over 50 rarely hear well above 12 kHz.

of frequencies is used extensively in amateur radio, especially in SSB (single sideband) transmissions.

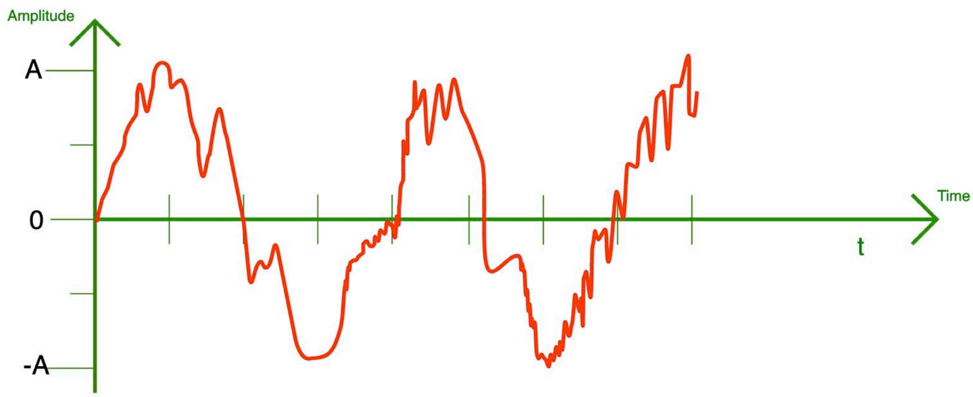

Figure 6-iv: Non-sinusoidal speech waveform. [EI9ILB]

6.2 Digital Signal Processing

DIGITAL SIGNAL PROCESSING, DSP, uses software to perform useful transformations, such as filtering unwanted signals, or noise removal, on the digital representation of the original analogue data.

There are many uses of DSP. Since its early days, DSP working at AUDIO FREQUENCIES (AF) has been used to improve the quality of received audio. Nowadays, DSP has replaced many traditional analogue transmitter and receiver functions. For example, DSP can perform modulation and demodulation of radio signals.

Because of the cost and complexity, DSP often does not work at RADIO FREQUENCIES (RF). Instead, DSP usually performs its functions at lower, INTERMEDIATE FREQUENCIES (IF), requiring additional electronic or software components to convert RF down and up from IF.[56]

In the more modern equipment, DSP works directly at RF, for example demodulating RF signal into AF representing speech without IF conversion steps. This latest approach is the foundation of software defined radio, SDR, further explained in section 6.5.

A typical use of DSP, shown in Figure 6-v, uses it as part of an analogue signal processing chain, i.e., where both the input and the output is an analogue signal. This analogue signal could represent speech at audio frequencies, and the function of such an AF DSP could be to enhance and improve the quality of the audio.

In an SDR, the analogue signal would represent radio waves. In that case, the RF DSP would digitally perform traditional radio functions, such as filtering or

56 IF used by modern DSP is usually 12–192 kHz, often 36 kHz. Compare that to typical amateur radio AF of 3 kHz, and RF well in excess of 1,000 kHz, e.g., 3–30 MHz used in HF applications, or 433 MHz on the popular UHF band.

demodulation. Conceptually, there is no difference between DSP designed for AF, IF, or RF. In practice, however, there are significant differences in the type of the necessary hardware, because of the vast difference in the frequencies at which it must operate: a dozen kHz vs. tens or thousands of MHz.

Figure 6-v: DSP in an analogue signal processing chain (analogue input and output) utilising direct digital synthesis (DDS) for reconstruction of analogue output. [EI6LA]

To use DSP, analogue data must be first DIGITISED, that is, converted into a sequence of numbers representing the amplitude of the original signal at regular, very small, time intervals.[57] This process uses hardware known as an analogue digital converter. ADC will be discussed in section 6.3.

DSP can be also used to process data that is already digital, such as some text to be transmitted using a digital mode, such as RTTY. In that case, there is no need to use the ADC. Such digital information can be directly provided to a specialised DSP that has been designed for this purpose.

After performing any required DSP transformations, the resulting digital signal may be used in different ways. It may be used to display a graphical spectrogram, such as the frequency waterfall chart shown in Figure 6-xiv on page 66.

Alternatively, if the input signal represented received digital data, the output from the DSP in a receiver may display the demodulated information, for example, the text that was received using a digital mode such as RTTY or Continuous Wave (CW).

Typically, however, the signal processed by the DSP needs to be converted back to an analogue form. For example, to hear it in a speaker, analogue voice audio needs to be reconstructed from its digital representation in a receiver. Or, in a transmitter, the output from the DSP needs to be converted to RF AC before it can be fed to an antenna. This reverse of digitisation is called SYNTHESIS or GENERATION. A common technique is Direct Digital Synthesis. Commonly, DDS uses two devices, a Numerically Controlled Oscillator (NCO) and a Digital Analogue Converter, DAC, although they can be contained in one physical integrated circuit. They will be explained in section 6.4 further.

57 For example, a CD and some downloadable music file formats, such as FLAC, store music using a sequence of numbers that represent amplitude (volume). They are measured at such short intervals that there are 44,100 numbers for each one second of music (44.1 kHz).

6.2.1 Time and Frequency Domains

An ADC converts analogue signal to a sequence of numbers that represent the signal's amplitudes taken at regular time intervals. Such way of representing information is called a TIME DOMAIN, because the horizontal axis of the plot shows the passage of time – see also section 5.1 Sinusoidal Signals.

An alternative way of representing this information would be to show the signal's frequencies on the horizontal axis, and the amplitudes of those frequencies on the vertical axis. That would be called a FREQUENCY DOMAIN plot. Knowing those two representations is useful for many aspects of radio, especially if you are planning on using waterfall displays, oscilloscopes, or signal analysers. Importantly, the representation of any real-world signals can be always converted between the time and the frequency domains any number of times without losing their detail.

Digital signal processing works with signals in both the time and the frequency domains because some transformations are easier in one than in the other.

The examples show sinusoidal signals in their time domains, i.e., the horizontal axis shows the passage of time. Figure 6-vi shows a 1 Hz sinusoidal signal, whose amplitude varies between -4 and 4. Figure 6-vii shows a higher frequency, but weaker signal: a 6 Hz wave with a smaller amplitude of -2 to 2.

What would happen if those two sinusoidal signals were added together?[58] You can see the result in Figure 6-viii. It shows a single, periodic, but no longer a sinusoidal signal. Notice how the overall amplitude of the combined signal now varies between -6 and 6.

58 There are many ways that waves can be combined. To keep this example simple, the two waves are added together. This is similar to how standing waves form on radio transmission lines, but it is different from the way signal mixers work. Mixers would multiply the waves together.

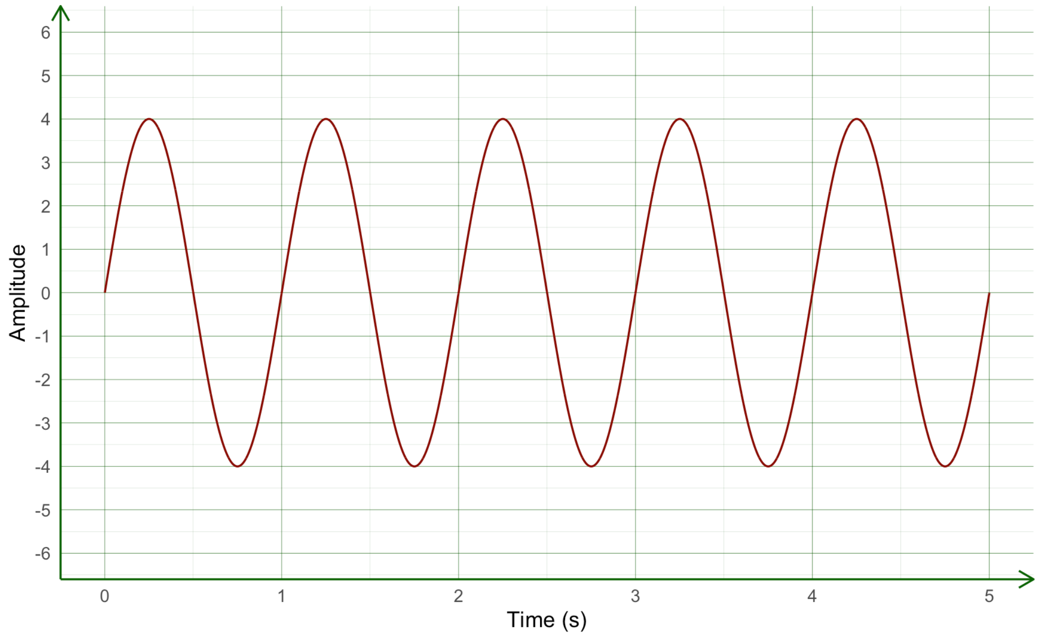

Figure 6-vi: Sinusoidal 1 Hz signal with an amplitude between -4 and 4. [EI6LA]

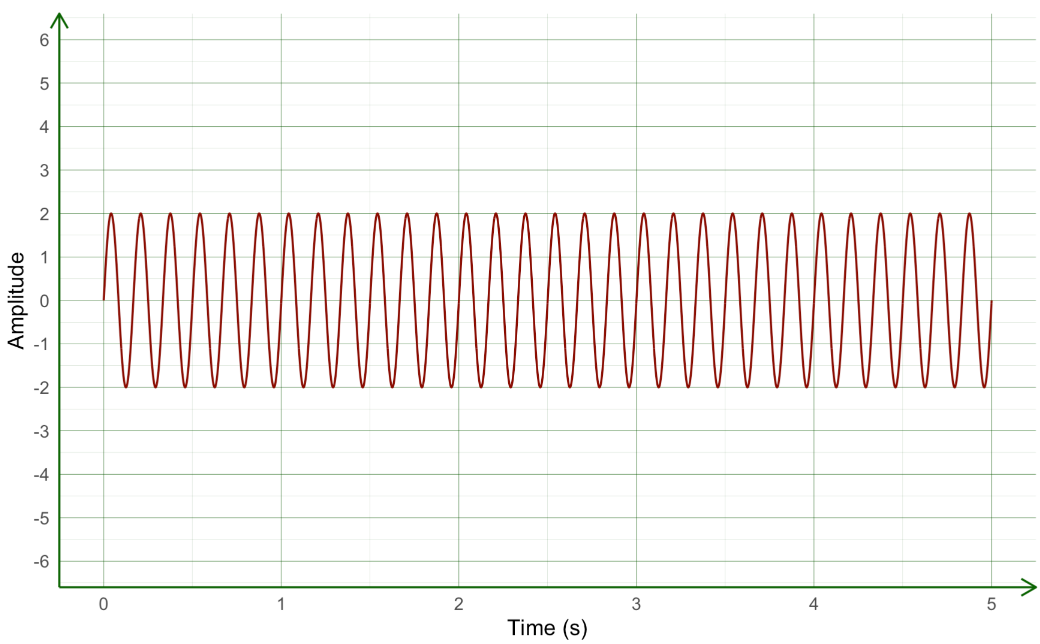

Figure 6-vii: Sinusoidal 6 Hz signal with an amplitude between -2 and 2. [EI6LA]

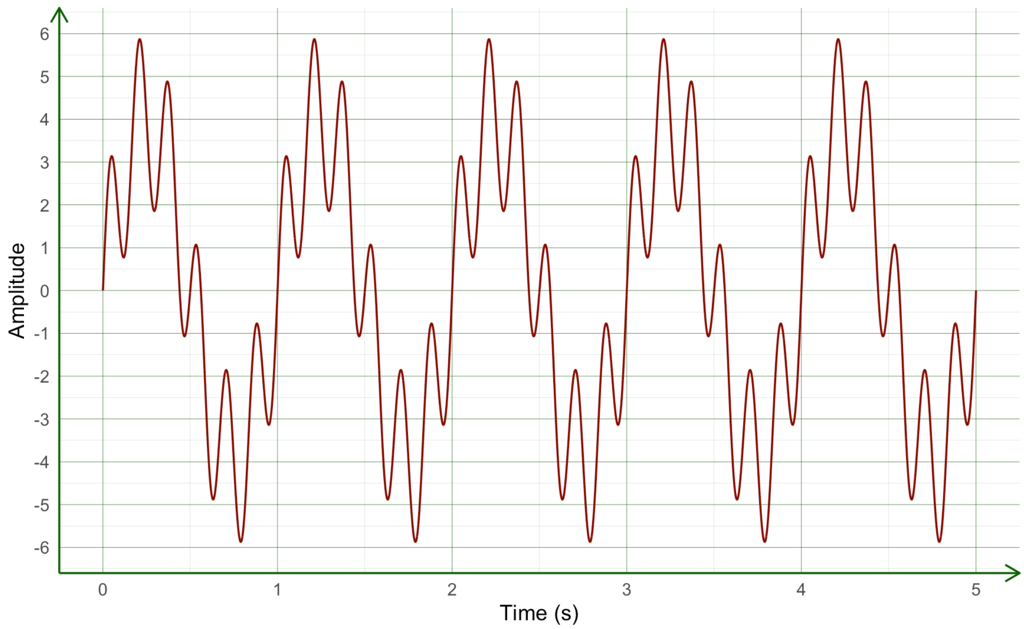

Figure 6-viii: Time domain plot of a non-sinusoidal signal composed of 1 Hz and 6 Hz sinusoids added together. [EI6LA]

The wave shown in the above example is relatively simple. You should be able to detect the two frequencies: the 1 Hz and the 6 Hz, even though this is a time domain plot, and it does not directly show any frequencies. See how the red line of the signal crosses the zero amplitude at exactly every one whole second – this is the 1 Hz frequency. You should be also able to see the 6 Hz signal in the plot, although it is a little harder to distinguish. You would need to count the number of the smaller cycles within each one second. You should notice that there are six smaller amplitude cycles within each second of the overall signal represented by the red curve.

Those two frequencies are much easier to see in the signal's frequency domain plot, which is shown in Figure 6-ix. It should be clear that there are two frequencies in the signal: 1 Hz and 6 Hz. This frequency domain plot also shows the amplitudes of both original signals.[59]

59 This frequency domain plot shows a *normalised* amplitude, i.e., representing a single cycle. Frequency domain plots can also show the aggregate amplitude, or sometimes the power, of the signal over the entire interval that was used to calculate them. As you can see from the time domain plot, the interval that was analysed in this case was five seconds.

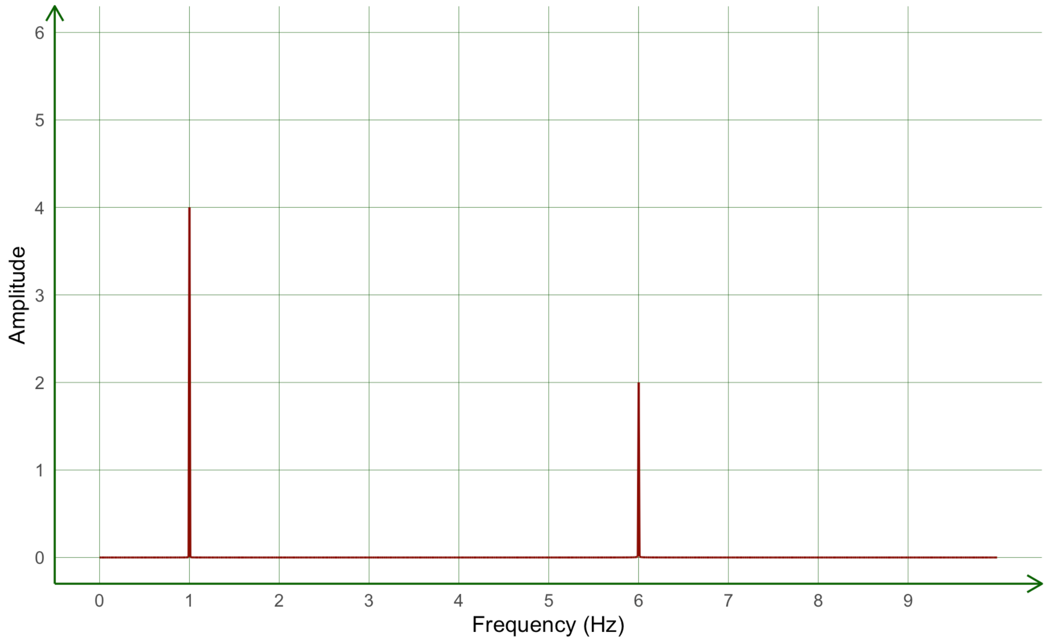

Figure 6-ix: Frequency domain plot of a non-sinusoidal signal composed of 1 Hz and 6 Hz sinusoids added together – compare it to the time domain plot in Figure 6-viii. [EI6LA]

Frequency domain plots of radio signals become very useful when the signals are more complex. A good example of a useful frequency domain plot is a waterfall display that can be found on modern receivers.

6.2.2 Fast Fourier Transform (FFT)

It is easy to transform a signal's time domain, shown in Figure 6-viii to and from its frequency domain, shown in Figure 6-ix. This conversion is one of the most important uses of a calculation known as the FOURIER TRANSFORM.

Fourier transform has many important uses in radio.[60] It is a fundamental principle of digital signal processing. It can convert any signal, including any non-sinusoidal signals, into a combination of sinusoidal signals. It can be thought of as extraction of the pure frequencies from the original, complex signal.

Fourier transform makes it easier to manipulate signals using digital signal processing. Some operations, such as filtering or noise removal, or modulation and demodulation of data, can be more easily implemented using signals transformed into their constituent frequencies, than in the time domain. Visualising a waterfall display, like the one in Figure 6-xiv shown on page 66 is as simple as performing a Fourier transform and displaying the results on a screen – like the two plots above.

60 Jean-Baptiste Joseph Fourier was an 18th century French mathematician and physicist. He developed the theory after which Fourier transform has been named. He studied vibrations, harmonics, and heat, and discovered the greenhouse effect.

Fourier transform is also used in reverse, to reconstruct the original time domain representation of the signal from its transformed frequency domain.

The most practical implementation of the Fourier transform in digital signal processing software[61] uses an algorithm called a FAST FOURIER TRANSFORM (FFT).[62] The main difference between a Fourier and a Fast Fourier Transform is that FFT works with digitised, that is sampled and quantised signals (see the next subsection). There are other forms of the Fourier transform but they are not as common in use in DSP.[63]

At its simplest, FFT takes a digitised, non-sinusoidal signal in time domain and calculates its frequency domain.[64]

FFT is used very widely. It is used by all mobile phones, digital radio receivers, CD players, MP3 and other music players, digital satellite receivers, and, of much interest to us, by software defined radio (see section 6.5). Plot shown in Figure 6-ix was created by running an FFT on the data shown in Figure 6-viii.[65]

Digital signal processing makes extensive use of FFT. Figure 6-x shows how FFT is used to convert an already digitised, but still time domain signal to its frequency domain, to simplify the software manipulation of that signal. Once manipulated, FFT can be used once again to reverse the transformation and to convert the processed frequency domain signal back to its time domain.[66] That reverse step is only necessary if there is further processing of the signal in its time domain, for example to send it to a DAC and then to a speaker.

DSP can, and often does work without relying on FFT. The main types of digital filters, Finite Impulse Response (FIR) and Infinite Impulse Response (IIR), which will be described in section 8.4.3, work entirely in the time domain. However, other

61 In computing, *software* means programs, while *hardware* means physical equipment.

62 In computing, the word *algorithm* means a portion of a computer program that implements an operation. Computer scientists study frequently used algorithms to find the best ways of implementing them. Fast Fourier Transform is a widely studied algorithm because it has many uses.

63 There are four types: *Fourier transform* (for continuous, non-periodic signals), *Fourier series* (continuous, periodic signals), *discrete time Fourier transform* or DTFT (discrete, i.e., sampled, non-periodic signals), and *discrete Fourier transform* or DFT (sampled, periodic signals). They are collectively known as the Fourier transform, however, it is only the last one, the DFT, that is used extensively, as it is the basis of the Fast Fourier Transform (FFT).

64 To be precise, the frequency domain that the FFT calculates for a given time domain signal is a little bit more than what is shown in Figure 6-ix on page 56. That plot shows the frequencies on the horizontal axis, and their amplitudes on the vertical axis. FFT also calculates the *phase* of each of those frequencies, which is usually omitted from such plots. However, that phase information is *necessary* when reconstructing the original time domain signal. In other words, FFT calculates the set of sinusoids, each described by its *frequency, phase,* and its *amplitude,* so that if they were added together, they would accurately represent the original signal.

65 These and several other plots in this guide were created using the R programming language and the *ggplot2* package. The conversion FFT was done using the *stats::fft* function. There are similar functions in popular programming languages, and in Microsoft Excel.

66 To reverse the FFT, i.e., to reverse the DFT, the discrete Fourier transform, one requires an IDFT – *inverse* discrete Fourier transform. Fortunately, FFT exhibits a useful symmetry in how it works. It can perform both the function of a DFT and an IDFT, with a very minor difference: it reverses the direction of the time axis when used as an IDFT, something that is easily accounted for.

types of filters, especially those for more advanced noise removal and audio enhancements, work in the frequency domain and require FFT.

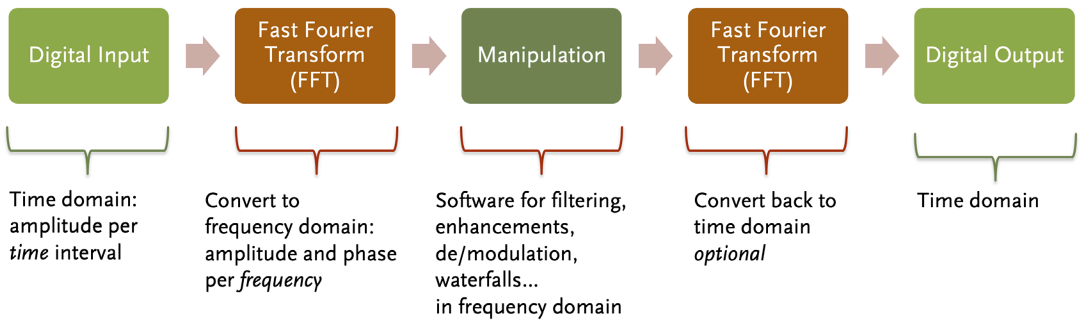

Figure 6-x: Digital signal processing using fast Fourier transform, FFT. [EI6LA]

6.3 ADC, Sampling, and Quantisation

Digital signal processing, both with and without a Fast Fourier Transform requires a digital input. ADC and DAC convert analogue signal to digital data and back. This section focuses on the ANALOGUE TO DIGITAL CONVERTER (ADC), also known as A/D, or A-TO-D. However, the main characteristics of an ADC, sampling rate and resolution, apply equally to the design and the workings of the Digital to Analogue Converter, DAC, which is discussed further below.

Figure 6-xi shows the two steps involved in analogue to digital conversion: sampling and quantisation.

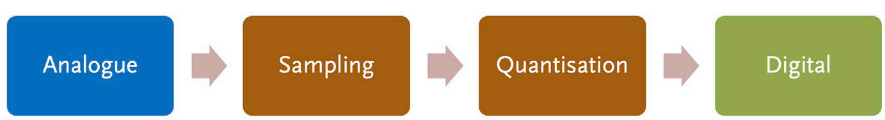

Figure 6-xi: Analogue digital converter, ADC, simplified. [EI6LA]

6.3.1 Sampling

SAMPLING is a process of measuring the amplitude of a continuous analogue signal, at very short intervals. The sampling intervals are so short that the measurement will be taken tens of thousands or even hundreds of millions of times per second![67]

67 Sampling theory requires not only short enough sampling intervals but also that the measurement is instantaneous. That is not possible in practice – each measurement takes some time, even if less than a nanosecond. That means that the measurement will not represent the amplitude at an infinitely small moment in time. Instead, it usually represents an *average* of the amplitude over the time it took to sample it. This leads to a sampling error known as the *aperture error*. Aperture, in this context, means the duration of the measurement. This will contribute, in a small way, to the noise floor of the ADC. It can be somewhat compensated for by *oversampling* the signal.

A SAMPLE is not yet a number – it is still an analogue measurement, but one that represent the amplitude of the continually changing analogue signal at a brief moment in time.[68]

You can imagine this process as if someone were using an old-fashioned, analogue voltmeter, one with a mechanical pointer moving over a round dial or a scale. This voltmeter would be measuring the voltage appearing on the cable connected to a microphone, or to an antenna, and whose signals we wish to sample. Sampling would be like freezing the image of the voltmeter in your memory, or perhaps by taking a picture of it, great many times per second.

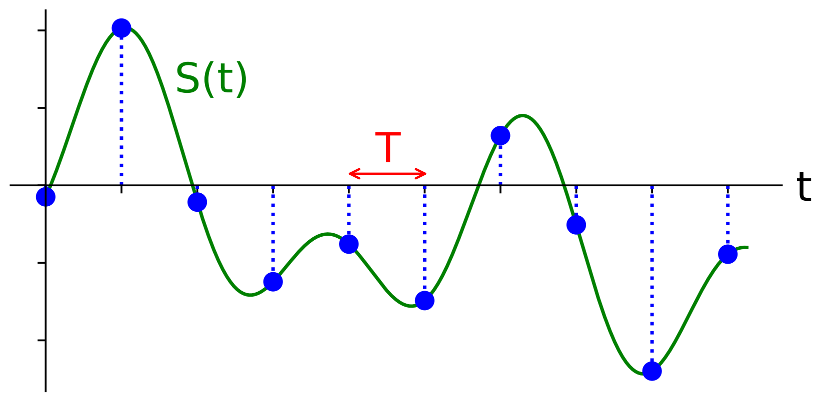

Figure 6-xii: Sampling a non-sinusoidal, continuous analogue signal (green curve) at sampling intervals of T (fraction of a second). Horizontal axis represents time (t) and vertical is the amplitude. Blue dots represent the samples.
[Image by Marc Lichtman KC3JTT, see page 375]

As shown in Figure 6-xii, the green line, which represents the analogue signal, is being sampled at small intervals of a fraction of a second. Notice that the blue dots, which represent the samples, are not always where the peaks and the troughs of the green line lie! They are sometimes below and sometimes above the minima and the maxima. This does not matter if the samples are taken often enough. Intuitively, you should recognise that the more samples are taken per second the more accurate the sampling is going to be.

6.3.2 Quantisation

The analogue sample that represented the signal at a moment in time needs to be converted into a number to become digital data. This conversion is known as QUANTISATION.

68 Technically, after sampling a *continuous analogue* signal, the samples represent a *discrete analogue* signal. They are not *digital* yet. In practice, the sample is represented by an as-yet unmeasured voltage of a capacitor, or some other electronic component that receives the voltages.

Like sampling, quantisation is implemented in hardware, which is one of the reasons why an ADC is always a physical device, and not software alone.[69]

To follow the analogy of the old-fashioned voltmeter, quantisation would be just like looking at the dial of that voltmeter and trying to figure out at which tick mark on the dial the pointer is pointing to. Each of the tick marks have a numeric label showing the voltage. If the pointer is pointing between any *two* tick marks, the quantisation process requires you to round the result by selecting the tick mark that is closest to the pointer. If the pointer is stuck below the bottom or above the top of the dial, perhaps because the signal was too strong or too weak for its range, you would select the lowest or the highest number shown on the dial.[70] Whatever the number you select is the number you would write down as the result of the quantisation process. Intuitively, you should understand that the more tick marks there are on the scale of the voltmeter the more accurate the quantisation process would be.

6.3.3 Sampling Rate and Resolution

The analogue signal has now been digitised: it became a series of numbers, representing amplitudes measured many times every second. Will those numbers be able to properly describe the original signal? Will there be any inaccuracies or errors?

There are two important characteristics of an ADC and a DAC that are related to the sampling and the quantisation steps: sampling rate and resolution. Together, they determine the bandwidth and the signal-to-noise ratio of the converter, and therefore its overall quality.

The SAMPLING RATE is expressed in Hz (hertz) and measures how many samples are taken per second. Sampling rate determines the BANDWIDTH, which is also measured in Hz. Bandwidth tells us how wide a portion of the signal's frequency spectrum the ADC or the DAC can work with.

The RESOLUTION is related to the quantisation step. It is expressed in the number of BITS[71] needed to represent one sample as a number. The more bits there are the higher the resolution. You can think of the resolution as the number of tick marks on the dial of our metaphorical voltmeter. The higher the resolution, the higher the SIGNAL-TO-NOISE RATIO (SNR)[72] and the dynamic range. SNR, measured in decibels (dB) tells us the quality of the output that the converter produces, i.e., how many

69 Quantisation can be implemented in many different ways. A *direct conversion* approach uses a series of comparators, i.e., a network of resistors of different resistances, tiny amplifiers, and a set of logic gates. Together, they find out which of the set of known voltages is the closest one to the voltage across a capacitor that was just charged during the sampling step.

70 This leads to *clipping*. Information is lost when that happens.

71 *Bit* is the most basic unit of quantity of information. It is a fundamental concept in information theory. 1 bit can represent two possible values: a zero or a one. 8 bits, also known as a *byte,* can represent 256 values, such as an integer number between 0–255. The word *bit* was introduced by Claude E. Shannon in 1948, even though the concept has been studied as far back as 1732 for the purpose of programming mechanical textile looms.

72 For example, an 8-bit ADC can record only 256 distinct values of the sampled signal (amplitude) and any values that fall between them must be rounded to the nearest one. A 14-bit ADC can measure 16384 distinct levels of amplitude, while a 16-bit one can measure 65536 values.

more times the converted signal is stronger than the noise. Decibels are explained in Chapter 9 Power Ratios and Decibels.

The DYNAMIC RANGE is related to SNR, and it is also measured in dB. It measures the ratio between the loudest and the quietest signals that the converter can work with. If you use an SDR receiver, you may be familiar with an overload or clipping indicator. It lights up when signals that exceed the dynamic range of the ADC are received and overload the converter, rendering no useful output, and distorting the signal.

If a converter does not have enough resolution – not enough bits – to represent all the important values, the quality suffers.[73] Audio can become coarse and noisy, or even no longer readable.

It is possible to have converters that have an impressive bandwidth but poor SNR, and the other way round.

6.3.4 Minimum Sampling Rate

A key design aspect of all digital signal processing is the number of necessary samples, in a second of time, to PROPERLY DIGITISE (perfectly) the original analogue data. The answer is given by the MINIMUM SAMPLING RATE, also known as the NYQUIST RATE,[74] not to be confused with the Nyquist frequency.[75]

The minimum sampling rate is twice the highest frequency[76] appearing in the analogue signal.

$$Minimum\ Sampling\ Rate = 2 \times Highest\ Frequency$$

The actual SAMPLING RATE f_s used by the ADC must be *at least* the minimum sampling rate, or *higher.*

$$f_s \geq Minimum\ Sampling\ Rate$$

For example, to perfectly digitise voice and music, which spans from 0 to 20 kHz (see section 6.1) the actual sampling rate must be twice that highest audio frequency,

73 This is known as a *quantisation error.* If the resolution is insufficient, intermediate but still useful values must get rounded to the nearest value that *can* be recorded. Information is lost in the process, and the resulting digital representation is no longer an accurate replica of its analogue original. The difference will manifest itself as noise created by the ADC. This can be alleviated by oversampling. In general, each one bit of resolution provides an approximately 6 dB improvement to the SNR.

74 Harry Nyquist, a Swedish physicist, and Claude Shannon, an American mathematician, gave rise to the Nyquist–Shannon sampling theorem, 1928–1948. It is one of the fundamentals of information theory and signal processing. See en.wikipedia.org/wiki/Nyquist–Shannon_sampling_theorem and en.wikipedia.org/wiki/Nyquist_rate.

75 Nyquist *frequency,* or *folding frequency,* is the *maximum* frequency (bandwidth) of an analogue signal that could be correctly sampled for a given sampling rate. It is equal to *half* of the sampling rate. If an ADC is sampling at the rate of 40 kHz, the Nyquist frequency is 20 kHz. Analogue signals above the 20 kHz frequency could not be sampled properly because they are higher than the Nyquist Frequency of that ADC. Older literature sometimes confuses the Nyquist rate and frequency. For the purposes of the exam only the minimum sampling rate, i.e., the Nyquist rate needs to be known.

76 Technically, it must be twice the *bandwidth* of the analogue signal. If an analogue signal contains all the frequencies from zero to the highest one, its bandwidth is equal to the highest frequency.

that is, 40 kHz, or more. Processing smaller bandwidth signals, such as speech, allows considerably lower sampling rates. Conversely, if one wanted to directly sample radio frequencies, up to, for example, Very High Frequency (VHF) signal at 144 MHz, the sampling rate would have to be quite high, at least 288 MHz. Unlike the 30 MHz upper range of High Frequency (HF), sampling VHF and above is still difficult.

If a signal is sampled at less than the minimum sampling rate, a loss of detail and quality will occur. Unwanted artefacts will be introduced, known as ALIASING. When minor, they can be heard as buzzing, ringing, metallic or a raspy sound, but they can also manifest as loud clicks, or as a distracting splatter which sounds like loud distorted echoes of a nearby transmission. Distortion gets worse as the sampling rate decreases. This issue affects both the sampling of and the synthesis of analogue signals to and from their digital representations.

The same problem will occur if the signal contains any frequencies higher than half of the actual sampling rate. For those reasons, the analogue signal that is being fed to the ADC must be very carefully filtered to ensure that there are no frequencies higher than half of the sampling rate used by the ADC. Otherwise, the unfiltered frequencies will appear in the digitised output as ALIASES: potentially loud, yet entirely new frequencies that are half, or another fraction of the unfiltered ones. This requires the use of analogue, electronic filters, known as ANTIALIASING FILTERS. The output of the DAC will also have to be filtered in a similar way.

6.3.5 Oversampling

The early 20th century discovery that sampling at the minimum sampling rate, i.e., at twice the highest frequency of the analogue signal is enough to properly represent the original signal, has been fundamental to all kinds of signal processing, not just DSP. It underlies digital photography, healthcare imaging, music, moving images, print – not only radio.

In an ideal scenario, if there is a definite limit to the highest frequency in the original signal, the resolution of the quantisation step is sufficient, the original signal has no noise, and sampling hardware is error-free, then sampling at a higher rate than the minimum sampling rate would not be harmful but brings no additional benefits.[77]

77 Nyquist–Shannon sampling theorem explains why it is *not necessary* to sample at a higher rate. When there are *two* samples for every change in the signal, i.e., looking at Figure 6-xii on page 59, there are two blue dots between every change of the direction of the green line (highest frequencies of the analogue signal) there exists *exactly one set of sinusoids* that could connect all of those blue dots. It is a like a jigsaw puzzle: there is just one way to match each other to make up the overall image. That set of sinusoids represents the *frequency domain* of the signal. Fourier transform allows it to be converted back to the original signal's *time domain* without any loss of information. This is an interesting symmetry between the world of analogue and digital signal representations. Neither is better, because there is always a practical limit to the highest frequency of interest, because of noise in the original signal, and more noise introduced by the circuitry and by the sampling and quantisation steps. It has been proven that the analogue and the digital representation of the signal are equivalent, without needing anything more than the *minimum sampling rate* and a *sufficient resolution* – under perfect conditions. See en.wikipedia.org/wiki/Nyquist–Shannon_sampling_theorem.

In practice, those requirements are very difficult to meet and OVERSAMPLING, that is, sampling at a higher rate than the minimum sampling rate is genuinely useful.

Oversampling reduces the impact of various quantisation errors, and it can also counteract errors caused when using an insufficient resolution.[78] Oversampling reduces the influence of noise in the original signal. It can also allow sampling of signals that have been filtered imperfectly whilst trying to impose the necessary limit to the highest frequencies in the sampled signal.[79]

For those reasons, practical ADC implementations tend to sample at a rate somewhat higher than the minimum sampling rate. However, benefits of oversampling quickly reach a limiting point.

6.4 DAC and Direct Digital Synthesis

There are two key scenarios where digital signal needs to be converted back to its analogue representation as AC. The first arises in an SDR transmitter and is explained in the next section. The second scenario has already been mentioned in the DSP section above. After some DSP processing of the digitised signal, it may need to be converted to analogue to be then output to a speaker.

This can be accomplished in several ways. One popular approach that serves both of those requirements is DIRECT DIGITAL SYNTHESIS, DDS. It is shown schematically in Figure 6-xiii. This approach combines the use of a Digital Analogue Converter, DAC, also referred to as D/A, or D-TO-A, with another component, a NUMERICALLY CONTROLLED OSCILLATOR (NCO).

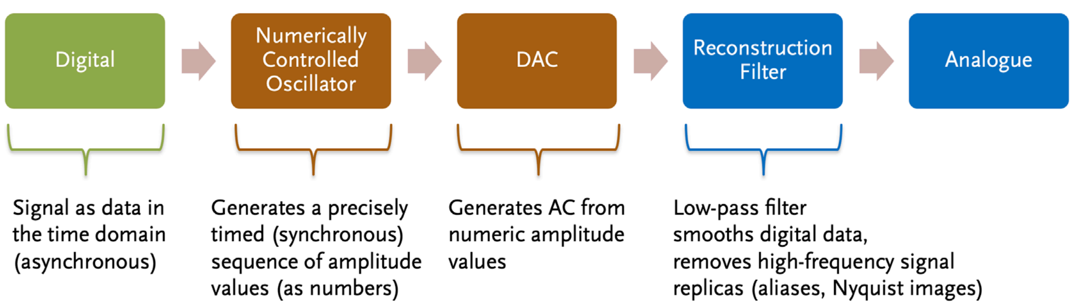

Figure 6-xiii: Direct digital synthesis using an NCO and a DAC. [EI6LA]

78 An example of that is a 1-bit ADC and a DAC. It performs quantisation that can take only two values (1-bit). Those values are either two fixed values, to represent an amplitude above or below some threshold, or, as implemented using *sigma-delta* encoding quantisation, where the value of 1 indicates that the sample has a higher amplitude than the previous sample, while zero means the amplitude has decreased. Such quantisation yields an unacceptably low SNR. To counteract that, significant oversampling is needed. Because the electronic circuitry of a 1-bit ADC is surprisingly simple they have uses, especially at audio frequencies.

79 One of the historical reasons why CD sampling rate was set at 44.1 kHz was that it used to be difficult to build filters capable of removing all the frequencies above the auditory limit of 20 kHz without losing some of the audible frequencies just below 20 kHz.

A digital signal, typically in the time domain, is fed to the NCO. The NCO delivers a precisely timed sequence of digital amplitude values that the DIGITAL TO ANALOGUE CONVERTER (DAC) then converts into AC. Because the DAC operates on the same sampling principles as the ADC, it is then necessary to filter out all frequencies above half of the sampling rate, [80] which is performed using a RECONSTRUCTION FILTER. That filter is a type of a low-pass filter that has the effect of smoothing the resulting AC. [81] It is always implemented using electronic circuitry rather than software. Low-pass and other filters will be explained in section 8.4.2 Filters.

The digital signal that is being fed to the NCO can come at varying speeds (asynchronously), dependent on the vagaries of the rest of the computer circuitry. It is a bit like reading music: a musician can read a sheet of music at any rate they want to. However, they must play the notes using very precise timings, synchronised to the beat of a metronome or to conductor in an orchestra. The NCO relies on the presence of a high-precision reference clock that all modern computerised devices have.[82] The NCO is like the musician who knows what kind of a note to play at exactly what moment in time.

The DAC is like the instrument the metaphorical musician plays. It generates the analogue signal, in the form of AC, based on the amplitudes that are being fed to it at their precise moments in time.

DAC can be constructed in many ways.[83] It is a relatively simpler devices than an ADC. There are also other ways to accomplish synthesis of analogue signals from their digital representation, without an NCO, especially at lower, audio frequencies.[84]

6.5 Software Defined Radio

SDR, or SOFTWARE DEFINED RADIO, uses software (algorithms) to implement all the key functions that traditional radios perform using electronic components. It can also perform new functions, thanks to the use of computer technology, that were not possible in the purely analogue era.

80 Those frequencies will contain unnecessary copies of the desired, lower frequency signals. If they were not filtered, the resulting signal would be a corrupt version of the original. Those copies are known as *Nyquist images*. They are just like the aliases generated by the ADC from poorly filtered input signals.

81 The reconstruction filter is sometimes also tasked with adjusting the amplitude of the resulting signal because the operation of some DACs provides a non-linear amplitude response.

82 Those reference clocks run at GHz and higher frequencies. Their precision is paramount to the quality of the synthesised signal. Their imprecision causes *jitter,* which can make the resulting signal frequency to vary. It can also cause alias-like artifacts to appear in the resulting signal. Interestingly, these clocks are still built using traditional, hardware crystal oscillators, see section 8.5.

83 Like ADCs, DACs are always implemented as hardware. One approach includes a network of switched resistors, acting as a voltage divider capable of delivering as many values of voltage as are required by the resolution of the DAC. The NCO provides a digital value of amplitude as voltage. Depending on that value some resistors are switched in or out of the network, generating the desired voltage for the duration of the sampling interval.

84 One such alternative uses a design known as a Phase Locked Loop (PLL) but DDS with NCO is stable and has less phase noise whilst being economical. See en.wikipedia.org/wiki/Phase-locked_loop.

While some aspects of signal processing are now easy to implement in software, for example noise reduction and some types of filters, others are still quite difficult. For example, software alone cannot be used for final stage high power amplification, and it is poor at rejecting strong out-of-band signals. For those reasons, contemporary SDRs combine the use of analogue circuitry, such as band-pass filters, and power amplifiers, with DSP, to deliver the best of both. As the technology matures, more analogue processing will enter the digital domain.

The input of an SDR receiver, and the output of an SDR transmitter, connect to an antenna. Recall that antennas convert radio waves to and from alternating current, AC. That means an SDR receiver must digitise, and so sample, the AC, while an SDR transmitter must generate, or synthesise, AC – at radio frequencies, such as 28 or 144 MHz. Sampling the AC amplitude, as voltages, at those frequencies is no different to sampling the AC that represents audio from a microphone. However, it requires more complex, faster hardware, because of the much higher frequencies and bandwidths involved, and the greater demands on resolution.

An SDR, therefore, is a hardware device that contains an ADC for a receiver (see 6.3above), and a DAC. An SDR transmitter could use an NCO DDS (see 6.4). Both SDR receivers and transmitters also have a processor,[85] that either performs the remainder of the DSP tasks, or that delegates those to an attached computer. The SDR device can be as small as a USB dongle, or like a desktop radio, or as large as the largest transceivers.

6.5.1 SDR as a Broadband Receiver

A popular use of SDR receivers that can be implemented using inexpensive hardware is that of a BROADBAND RECEIVER that provides waterfall spectrogram displays, like the one shown in Figure 6-xiv.[86] Broadband, in this context, means a receiver that is simultaneously receiving a broad range, or a band, of frequencies. A conventional radio receiver is tuned by the operator to a specific frequency that they wish to listen to. A broadband receiver, however, can receive an entire band, even several bands at the same time. This would not be useful for listening purposes, but it is essential for charting waterfall plots that display what is happening on the entire band.

85 In addition to using common computer processing units, i.e., CPU microprocessors, it is increasingly popular to employ dedicated hardware processors that are faster at performing routine signal processing computations, such as the FFT. Such hardware processors can be custom-built using Field Programmable Gate Arrays (FPGA) or Application Specific Integrated Circuits (ASIC) or can use commercially available DSP integrated circuit chips. They can be found in recent SDR transceivers.

86 Waterfall display, a type of a *spectrogram,* shows signal amplitudes at individual frequencies, allowing an entire band to be analysed at a glance. The signals are plotted line by line as the time passes. Because of the way the plot scrolls down it resembles a waterfall. SDRs can be used to create waterfall displays for computer screens. Modern receivers have built-in waterfall displays. There are also standalone devices called spectrum analysers, spectrum scopes, panoramic adapters, or panadapters. See en.wikipedia.org/wiki/Spectrogram.

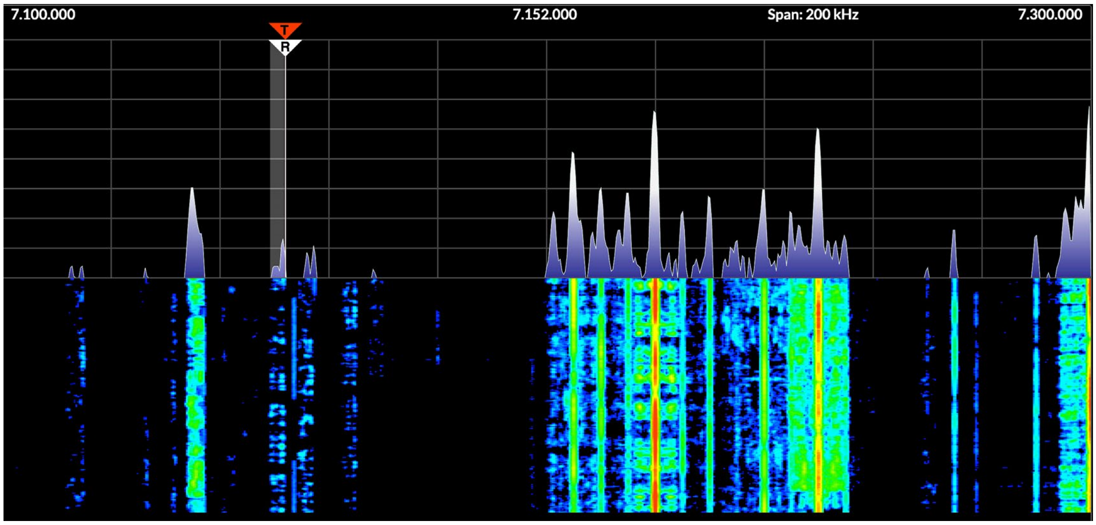

Figure 6-xiv: Spectrogram (upper half) and a waterfall (below). Amplitude of AM broadcasts shown as values on the y-axis (above) and colour (below). Frequency on x-axis. SSB (LSB) amateur radio transmissions on the left, and commercial AM on the right above 7.200 MHz. [EI6LA]

Because this use of an SDR has low requirements of resolution and dynamic range, and since audio quality is of no concern when one is not listening but merely looking at a chart, the necessary SDR hardware is inexpensive. Some radios contain SDR technology just to offer such displays. However, SDR can be also used to build receivers and transmitters that offer very high-quality audio and signal processing.

There are more examples of waterfall plots (frequency domain plots) of different types of signals in Chapter 11 Modulation and Modes.

6.5.2 Modern Transceivers and SDR

SDR can be much more than DSP for radio frequencies. It can be used to build entire receivers and transmitters. Software can provide almost all radio functionality: frequency tuning, filtering, mixing, signal modulation and detection, noise suppression, and convenience features, such as memories, waterfall displays, remote control, Computer Aided Transceiver (CAT) control, and even a user interface with menus and touchscreens.

Nowadays, radios use SDR technology in two ways: a hybrid design that combines an analogue receiver and a transmitter with DSP, or a fully digital design that performs almost all radio functions using software.

All modern transmitters and receivers extensively use DSP for signal modulation (generation) and demodulation (decoding) purposes. Commercially available radios

have used the hybrid design since approximately 1995. Traditional, all-analogue electronic transceivers have not been commercially produced since about 2005.[87]

6.5.2.1 *Fully Digital Design*

In a FULLY DIGITAL design, software performs almost everything that a radio must do. Some functions cannot be done using software at all or are not yet economical. Electronic circuits are necessary for power amplification, for filtering of strong out-of-band signals, for the ADC, including its antialiasing filter, and the DAC, a reconstruction filter, and of course, for the processor that runs the SDR software itself.

Fully digital receivers use DIRECT SAMPLING of the AC representing the RF signal received by the attached antenna. The ADC produces a digitised signal translated to a lower Intermediate Frequency (IF), or even to a BASEBAND signal at zero Hz frequency. The baseband or IF is passed to the DSP for demodulation. Alternatively, the DSP can work on digitised signal at RF. This is explained in section 13.6.1.

Fully digital transmitters generate the output RF waveform digitally. There are different methods using a combination of high precision timing sources (computer clocks) and specialised integrated circuits (IC). A popular approach is DDS. In this design, the DSP performs modulation, usually at the same frequency that is used by the receiver, i.e., at baseband, or at a low IF, or, in more advanced designs, at RF. This modulated signal is passed to DDS, and eventually to the antenna. This will be explained in 12.10.1.

Because the minimum sampling rate (see 6.3.4) is so high at RF, these approaches require advanced ADCs and DACs in order not to compromise on having to lower their resolution, and in turn, reduce SNR and the dynamic range, and the overall quality.[88] At present, this is only possible up to HF. Fully digital VHF and Ultra High

87 Since their beginnings, radios relied on analogue, electronic circuitry for generation of all modulated signals. 1995 was a milestone year. In that year, ICOM released IC-775DSP, Yaesu FT-1000MP, and Kenwood TS-870. These three radios all used a low final IF around 10–15 kHz in the receiver to feed the DSP for IF processing, demodulation, and audio. In the transmitter, the DSP would produce a modulated signal at that low IF, which was subsequently converted to the final frequency via the usual processing chain consisting of frequency mixers, multipliers, and converters. The TS-870 even used DSP to shape the CW waveform. More expensive, top-end radios gradually switched to using DSP for both receivers and transmitters. Except for IC-718, which remains in production, the last all-analogue ICOM radio, IC-781, was discontinued in 1999. Budget-priced radios took another ten years to complete the switch to DSP and SDR-based reception and transmission. As a rule of thumb, commercially available radios introduced after 2005 use DSP for all modulation and demodulation, even if they are hybrid and not yet fully SDR-based. The IRTS would like to thank Adam Farson VA7OJ, Peter Hart G3SJX, and Rob Sherwood NC0B for providing the historical information about radio design.

88 Less expensive SDRs offer a compromise between high direct sampling rates and lower resolutions. For example, currently popular *SDRplay* devices offer either a lower direct sampling rate of up to 6 MHz with up to 14-bit resolution, or a higher sampling rate of over 9 MHz but with only an 8-bit resolution. USB dongle-style SDRs that offer direct sampling may only offer 8-bit resolution. Choice is further complicated by other aspects of design. Less powerful processors may offer a seemingly good sampling rate and a resolution but at the price of introducing significant *latency* that adds a noticeable delay to the processed audio signal. This may be a problem for some operators but not for other purposes, such as plotting waterfall charts.

Frequency (UHF) designs are still somewhat compromised because of the limitations of the currently available ADCs and DACs.[89]

More economical designs digitally convert RF to a lower IF before performing sampling and passing the sampled data to the DSP, which is then used to demodulate the signals. To transmit, DSP is used to modulate the signal digitally, and DDS can synthesize it at the low IF. Subsequently, IF is converted to the higher, desired RF.

This frequency conversion can be done fully digitally using downconverters for receivers, and digital upconverters for transmitters. Frequency conversion can be also incorporated into the sampling and synthesis hardware.[90] However, if the frequency conversion uses traditional analogue circuitry, then the design is considered to be a hybrid SDR.

6.5.2.2 *Hybrid Design*

The down- and up-conversion between IF and RF can be also performed using more traditional, analogue electronic components. The currently popular design, often referred to as HYBRID SDR, relies on the principles of a traditional receiver and a transmitter sending and receiving low IF signals to DSP.

Such a hybrid design radio often uses a superheterodyne receiver, see 13.6.2 Hybrid SDR Receiver. The analogue circuitry can be also thought of a signal preconditioning stage, before it reaches digital processing. The output of a superheterodyne is a good quality lower IF. The IF is passed to DSP that does not need to have a very high sampling rate, because of the low frequency of the IF. In return, the otherwise simpler DSP can provide a high resolution, therefore offering very good dynamic range and SNR in a more economical way than with direct sampling.

Just like in the fully digital design, DSP performs demodulation of all modulation modes, as well as any audio enhancements. A key advantage of this approach is that

89 Icom IC-9700 uses direct under-sampling on 144 and 433MHz, while mixing 1.2 GHz (23 cm band) down to 300 MHz before under-sampling. Because its ADC is under-sampling at less than the minimum sampling rate, additional processing is required to remove aliasing artefacts. As of January 2024, there are no commercial amateur transceivers working at Nyquist frequencies on VHF and above.

90 ICOM IC-7300 claimed to be the first widely available, commercial fully digital SDR-based transceiver that has used this approach in a self-contained radio, not requiring the use of a computer, for both reception and transmission. IC-7300 performs direct sampling of the radio signal, outputting digital data at a lower IF of only 36 kHz, then using DSP to demodulate it. That IF frequency is relatively close to AF, which permits this transceiver to use a more traditional, high-quality audio-class DSP in its remaining processing stages. IC-7610 uses a similar design but with a higher resolution, using a proprietary FPGA circuit. Other commercial transceivers, such as FlexRadio Flex-6400, perform a direct sampling that outputs digital baseband without that intermediate modulation, that is, at zero Hz. This more complex hardware design claims to be flexible and upgradeable since more processing is done by the software, rather than in the hardware. There are *many* other differences between them. IC-7300 looks and operates like a classic radio, while Flex-6400 requires a computer or an additional control panel; the former uses 14-bit while the latter has 16-bit resolution. FT-710 was the first direct sampling Yaesu transceiver, and K4 was the first one from Elecraft. In these still early days of SDR there are different approaches towards sampling, demodulation, and user operation, however, basic understanding of designs, sampling rates, resolution, and processing speed, will help you make informed choices when choosing one.

only one receiver circuit is necessary for all the different modulation types, rather than needing a different receiver for each, as used to be the case in earlier years.

Transmitters in hybrid SDR transceivers use DSP to modulate signals and output IF. The low frequency of the IF is then converted to the required RF using analogue components, such as a frequency converter, or a mixer, just like in a traditional SSB transmitter, see 12.10.2 Hybrid SDR Transmitter with IF DDS.

Almost all commercially available radios have used the hybrid approach for many years.[91]

Older transceivers may use DSP to improve the quality of the audio signal. However, that is not a form of SDR because the DSP is not working with RF signal at all. In those radios DSP is merely used to augment the AF.[92]

To summarise, SDR has been an essential part of modern transceivers for quite some time. Because it is software, it enables manufacturers to update their designs quickly. It can be used directly from a computer or as a building block of receivers and transmitters. Time will show what is the right balance of software-defined vs. electronic circuitry to achieve our expectations of ultimate quality, reliability, and cost. It is an interesting area for experimentation, with much still to be discovered, especially for those with some programming or IT skills and those interested in electronics that fulfil functions that SDR still cannot perform.[93]

Please note there is a further discussion of SDR, including block diagrams, in sections 12.10 Modern Transmitters and SDR, and 13.6 Modern Receivers and SDR.

91 The current commercially available hybrid design transceivers include: Elecraft K3 and Kenwood TS-890S. Yaesu FTDX-10 and FTDX-101/MP are hybrid designs with direct sampling of 9 MHz IF.

92 Many transceivers produced commercially since early 1990's have some form of DSP for audio processing, for example, ICOM IC-706 MKIIG or IC-756 Pro.

93 For a basic introduction to SDR using the Python programming language see pysdr.org and for a more advanced, C++ SDR framework see www.gnuradio.org however, if all you would like to do is to use (rather than program) an SDR over the web, at no cost, have a look at SDR receivers shared by other amateurs and listed at rx.linkfanel.net and at websdr.org. Search the Internet for other web-based SDRs – there are many.

7 Radio Waves and Spectrum

FOUR EXAM QUESTIONS · SECTION A3

This chapter explains concepts, such as electromagnetic fields, radio waves, and radio spectrum, which are fundamental to both the radio theory and to its day-to-day use. It is related to exam section A3, however, it would be hard to pass the remainder of the exam, especially A1, A2, A5, A6, and A7, without a good understanding of the concepts covered in this chapter.

7.1 Radio Waves and Electromagnetic Radiation

The word *radio* is related to the word *radiation*. Radio waves are a type of electromagnetic radiation which is invisible to us. Radio waves transfer power over long distances. They travel through the air almost at the speed of light, and at the speed of light, which is approximately 300 000 km/s, in vacuum.[94] The speed of light is represented by lowercase letter c which you can see in some formulae.

Radio waves can pass through many materials, including buildings and the human body. They interact with many materials in different and interesting ways. It is important to us how radio waves interact with conductors, including copper, from which antennas are made. As radio amateurs, we are also very interested in the way radio waves interact with the soil of the ground, the water of the seas, and some layers in the atmosphere – all of which reflect or refract some radio wave frequencies so that they can travel far around the world. You will learn more about the way antennas convert AC to and from radio waves in Chapter 15 Antennas. The mechanisms by which radio waves travel will be discussed in Chapter 16 Propagation.

There are many other types of electromagnetic radiation. Some that you already know are visible light that people and animals can see, infrared radiation that we feel as heat, microwaves that can cook food, or x-rays that can pass through the human body to produce an image of bones and organs. In all these cases, the power transferred by the radio waves performs different types of work, such as inducing electric currents in conductors, x-ray sensors, or the retina of your eye, or causing matter to heat up.

94 Speed of light, c, is 299 792 458 m/s, usually rounded up to 300 000 000 m/s. You may find it helpful to observe that 300 000 000 m/s = 300 000 km/s = 300 Mm/s. Although you will never see a reference to Mm (megametre) in day-to-day life, noting this may be useful when you consider why the number 300 appears in the calculations involving MHz. The metric prefix M, mega, which means 1 000 000 (1 million), is the common to both the speed of light and the frequency when expressed as 300 Mm and 1 MHz. See also wavelength and frequency conversion formulae on page 41.

7.2 Electromagnetic Wave

An ELECTROMAGNETIC WAVE is called electromagnetic because it can be explained as an interaction between ever-changing electric (E) and magnetic (H) fields.[95]

These two fields' amplitudes (strengths) oscillate between being very strong, then zero, and then very strong again, but in the opposite direction. These oscillations are perfectly synchronised. They are perpendicular, that is, at right angles, 90°, to each other, and to the direction of travel of the electromagnetic wave that is propagating far away from the transmitting antenna. They PROPAGATE at the speed of light.

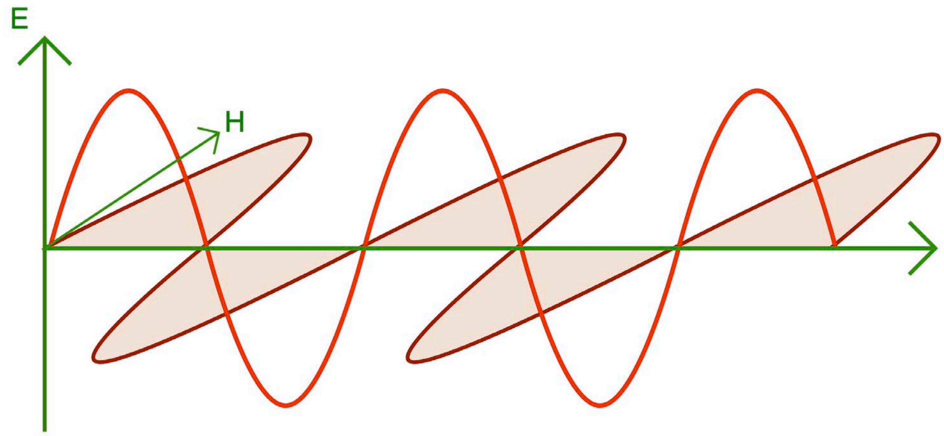

Figure 7-i: Electromagnetic wave consisting of an electric E field and a magnetic H field, showing the oscillations of their amplitudes as the wave propagates. [EI9ILB]

To understand an electromagnetic wave, it is important to know that the fields' amplitudes and directions are oscillating at every point in space that they pass through. They are not stationary. If they were not oscillating, the fields could still be felt close to their source, and even at some not-too-distant point. However, no electromagnetic wave would radiate to carry its energy with it, and long-distance radio communication would not be possible.

Because the two fields are so closely related, together they are known as ELECTROMAGNETIC FIELDS (EMF). Note the uppercase abbreviation EMF as opposed to lowercase *emf,* which stands for *electromotive force,* introduced in section 3.4.

The later section 15.2 Near and Far Antenna Fields explains that the EMFs near an antenna behave differently from what happens further away from it. That will help you understand how safety is affected by your distance from the antenna. It will also assist in evaluating antenna performance while designing or troubleshooting them, and when looking for the best location where to place them.

95 Ever-changing from the perspective of an object that is not moving with the wave, for example an antenna. This guide presents a *simplified* view of *classical electromagnetism,* dispensing with the detail or the precision required to describe its relativistic interpretation. To better understand electromagnetic waves, exceeding the scope of the HAREC, see section 30.1 Technical for further reading.

7.3 Fields and Wave Formation

Please note that this subsection, 7.3, *is not part of the exam syllabus.* It provides a high-level explanation of the physical concepts of fields and waves to make the remainder of the subjects easier to study. If you find these explanations confusing rather than helpful, please skip over this section to 7.4 Frequency on page 82.

7.3.1 Force Fields

In physics, electric and magnetic fields are known as FORCE FIELDS. They act upon every point in space. Every point can be described by the strength and the direction of the field's force acting upon it. The force's effect is mechanical. It can move electrons in a conductor in the force's direction at that point. It can even move some bigger objects. The arrows and their colour, shown in Figure 7-ii, show the directions and the strengths of an electric force field surrounding two electric charges, a negative and a positive one. It is like a magnetic field pattern that can be seen when iron filings are sprinkled around a magnet.

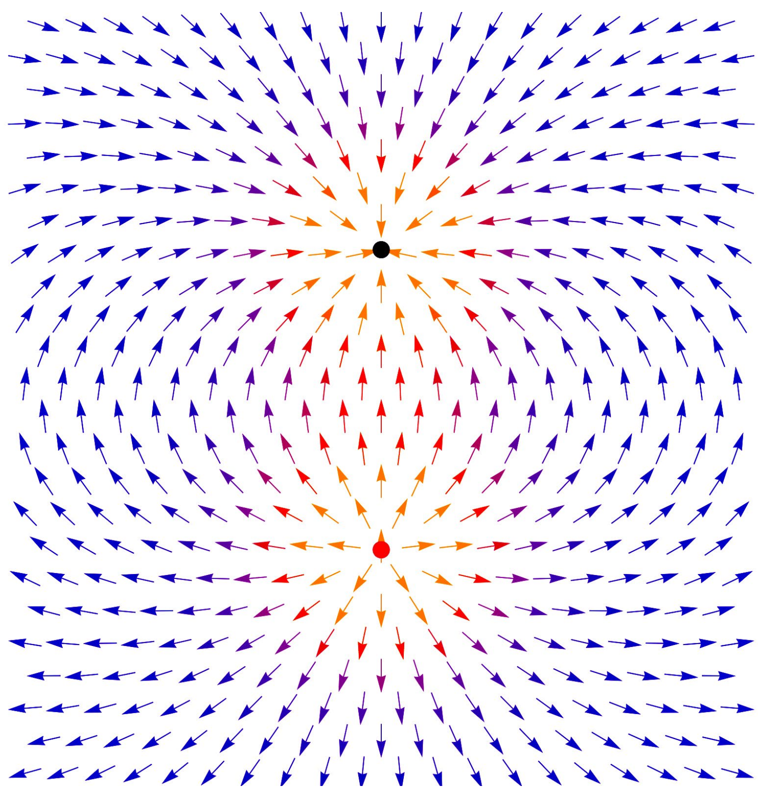

Figure 7-ii: Static electric field surrounding a negative charge (black, above) and a positive charge (red, below). Arrows in this vector plot represent the direction that would be applied by the force to each point in space. Colour indicates the strength of the force, from blue (weak) to orange (strong). [Image by Peter Zollman, see page 375]

These force fields can also cause new electric or magnetic fields to appear, but only if the fields are changing, i.e., if the strength or the direction of the force that the field exerts is changing.[96]

7.3.2 Static and Steady Motion Fields

Non-changing fields are known as STATIC FIELDS. Static fields do not transfer energy from their source to a destination – unlike radio waves, which are fields that are changing all the time. A magnet, for example, has a STATIC MAGNETIC FIELD around itself. It is also known as a MAGNETOSTATIC FIELD. You can feel its force by bringing an iron (ferrous) object close to it and by resisting the pull of the magnet. If you place the iron object on a wooden board, and the magnet on the other side, the object will move when you move the magnet. However, the object does not acquire energy from the stationary magnet, unless you move the magnet. When you move it, *you* are the cause of the change of the magnetic field around the object. The object follows that change.[97] Your work changed the field. The changing field moved the object. As a result, your energy was transferred to the object by moving it from a standstill and giving it speed.

A STATIC ELECTRIC FIELD, also known as an ELECTROSTATIC FIELD, or as STATIC ELECTRICITY, is similar. If you get static electricity in your hair, or on a sheet of cling film, or a woollen jumper, they may attract or repel themselves and other objects. Your hair may be standing up, the piece of cling film just keeps getting stuck to itself or to your finger as you try to shake it off, or the jumper crackles when you take it off. A static electric field is exerting a real force on those objects, just as the magnet exerted a magnetic force. However, unless you expend your own energy, for example, by moving the stuck objects, or trying to separate them, no energy is transferred, and no work is done.

In essence, by changing the fields, energy can be transferred to perform work at a distance. This would also happen if instead of moving the sources of the electric and magnetic fields the fields were changed in some other way, for example by introducing another magnet, or by increasing or decreasing the electric charge. Some energy would need to be expended to change the fields to see an effect on the objects they were acting upon.

Changing fields can also INDUCE currents to flow in conductors, like in a dynamo whose rotating [98] magnet changes the magnetic field, which induces an electric

96 In this context, the correct term for such a changing field is a *time-varying* field. Its strength or direction varies as the time passes, all the time.

97 If you start moving the stationary magnet horizontally, you will give the object some *kinetic* energy and the object will gain a *momentum*. If you move it vertically, you will also give it some *potential* energy by resisting the force of gravity. In both cases, you will first have to accelerate the magnet from a standstill, changing, or varying the magnetic field. In the horizontal case, if there were no friction, the magnet and the object would have continued moving on their own with no need for any further work to transfer energy to it. In the vertical case, you would need to continue the work and keep expending your energy to counteract the pull of gravity as you move the magnet and the object higher.

98 Steadily rotating objects are not just moving steadily, but they are in a state of acceleration. You can feel its effect as a centrifugal force pushing you sideways when you turn a car around a corner.

current in the nearby wire. Changing currents can also create changing fields. For example, in an electric motor, AC flowing through the motor's wire windings creates changing magnetic fields, whose changes turn the shaft of the motor.

Any changes to the fields will be felt both near and far from their source. However, the change is not felt instantly. The change, just like the fields themselves, propagates at the speed of light. Even though the speed of light is very high, the change still takes time to propagate. For example, a change of the magnetic fields on the surface of the Sun will take about eight minutes to travel before it is felt on Earth, because light takes approximately eight minutes to travel the distance between the Sun and Earth.

Steadily moving (in a straight line, not rotating) sources of electric and magnetic fields cause the fields to change in a steady manner. Static, or steadily changing fields can be felt near to their source, but their strength drops much too rapidly at a distance. Even though considerable energy may be expended to change them, steadily changing fields get too weak to be useful far from their source. That is why movement of even the strongest magnets only affects objects that are close to them.

Figure 7-ii shows that the directions of the forces of a static, or a steadily moving,[99] electric field point outwards from the positive charge, making increasingly large loops, before returning to the negative charge, to which they also point in a somewhat perpendicular manner. If you were to connect the arrows you would see field lines that always start and end at the charges. Even the lines suggested by the arrows that point almost vertically down and out of the bottom of the plot will eventually turn around to return to the negative charge, re-entering from above of the plot, pointing almost vertically towards the negative charge. Except for the area immediately between the charges, the majority of those field line loops are very long. As a result, their strength is spread over a very large area, which is one of the reasons why static fields get very weak at distances further from the source. Field lines of a static field are never free from the charges. If the charges were in a wire, the field lines would touch the wire.

7.3.3 Radiating Fields

If the movement of the field's source is not steady, because the source is accelerating or decelerating, the fields will change their shape radically. They will also acquire a special property: they will detach from the source and RADIATE ENERGY away from it in the form of an ELECTROMAGNETIC WAVE. They will take some of the energy from the source and carry that energy with them far away.

Importantly, while the strength of the radiating fields reduces as they propagate away from the source, it reduces only a little, in comparison to the strength of the static or steadily changing fields.[100] A kilometre or so from an amateur radio antenna

99 Static (not moving) things and those in a steady motion, i.e., neither accelerating nor changing direction, generally behave in the same ways. They are usually indistinguishable in physics. Albert Einstein summarised this discovery in his theories of relativity when he studied electromagnetism.

100 Strength of static fields drops at the square of the distance $1/d^2$ while the strength of the radiating fields reduces only at the rate of the increase of distance $1/d$ rather than its square. This makes a *very* big difference at distances that matter to radio communication.

the strength of the static or steadily changing fields is no longer felt, while the radiating fields can be felt strongly at tens of thousands of kilometres or more. This is also the reason why the fields surrounding an antenna have different properties in the near vs. the far regions around it.[101]

OSCILLATION is the most important type of a non-steady movement of a field's source that causes it to radiate as radio waves.

For a given point in space, a radiating field's strength or direction does not remain constant, but it oscillates. The strength, at that point, first increases quickly, then more slowly, until it reaches a point of the maximum strength, its maximum amplitude, when there is no further increase. The field strength now starts decreasing, first slowly, then quickly, until it reaches zero. At that very moment in time, the direction of the field's force reverses, and its strength, once again, increases quickly, then slowly, reaching the maximum in that opposing direction, just before it starts weakening again, till it reverses the direction as it once more crosses zero, and so on.

The strength of a radiating field increases or decreases a little faster or a little slower than a moment ago, at all times. There is no steady change. As a result, the force of a radiating field is able to accelerate and decelerate electrons that may find themselves within the field, even very far from the source. This is how a receiving antenna works.

An easy way to generate such an oscillating field is to feed a sinusoidal alternating current, AC, into a wire, the transmitting antenna. This causes an oscillating potential difference along the antenna, causing the electrons in the wire and their electric charges to accelerate and decelerate, and change their direction, twice in every oscillation, when the potential crosses the point of zero amplitude every half cycle. The acceleration and deceleration of the charges (electrons) is the reason why an electromagnetic wave forms at the antenna and propagates away from it. This is how a transmitting antenna works.

7.3.4 Formation of the Wave

The final piece of the radio wave puzzle is to get a glimpse of why those oscillations of charges (electrons) cause the fields to radiate away from the antenna, rather than remaining attached to it, as was the case for the static fields. A plot of a radiating field can illustrate the shape and the behaviour of the force.

A series of electric field force vector plots is shown on the next four pages to explain how the electromagnetic wave forms. Five stages of the first half of the cycle is explained in some detail, stepping in time every 1/8 of the cycle, i.e., every 45° of the phase of the AC.[102]

Figure 7-iii shows the electric field surrounding an active dipole antenna at the very start of the cycle, when the voltage between the ends of the antenna is at its maximum. This is time zero, t=0. In terms of the phase of the AC, this is the 0° phase.

101 This subject will be explored in section 15.2 Near and Far Antenna Fields.

102 A step-by-step version of a similar diagram is in *Orfanidis,* section 15.5, and in *Balanis,* section 1.3.2, see 30.1 Technical Resources. There are further animations at en.wikipedia.org/wiki/Antenna_(radio).

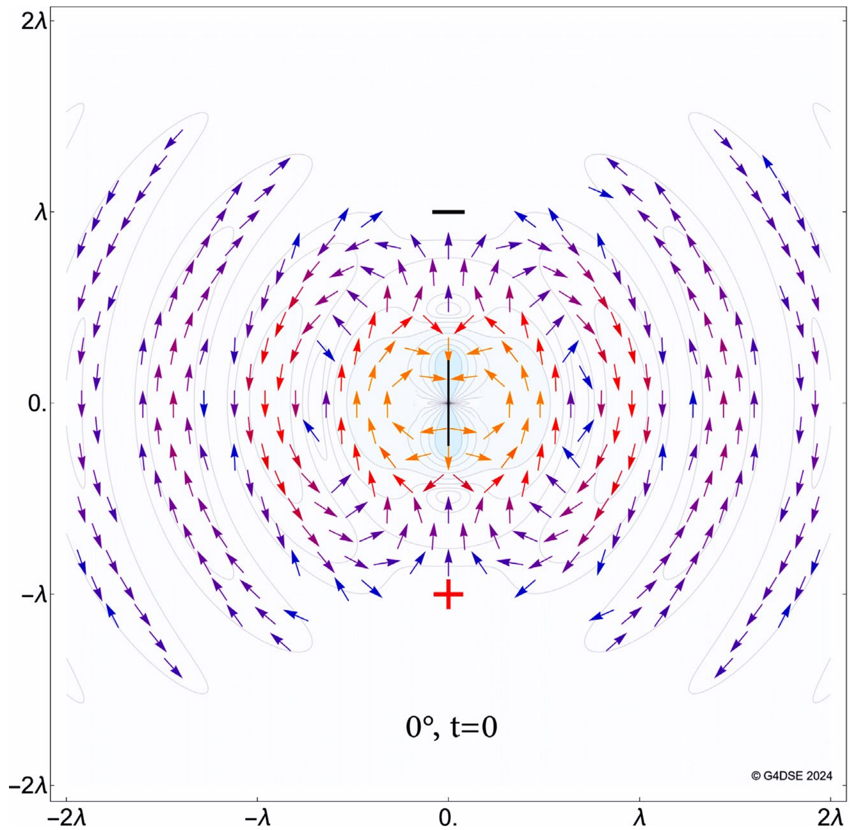

Figure 7-iii: Electric field surrounding an active, vertically oriented half-wave dipole antenna, represented by the thin line in the centre. Plot shows the start of a new AC cycle, the 0° phase, a moment in time when there is maximum voltage between the ends of the antenna. Positive at the bottom and negative at the top of the wire. [Image by Peter Zollman, see page 375]

Notice that close to the antenna, at this moment in time, t=0, at maximum voltage between antenna's ends, when the just-decelerated electrons have momentarily come to a halt, the closest fields, indicated by the orange arrows, directly point from and to the antenna, touching it – similar to the field lines of a static field.

On the other hand, the lines formed by the arrows a bit further from the antenna are very different from the static field's lines shown in Figure 7-ii. Instead of pointing outwards at right angles from the source, the radiating field's lines are becoming straighter and more parallel to the antenna the further they are from it. The direction of the lines also points up and down, mirroring the orientation of the antenna, rather than pointing towards and away from it. Most interestingly, perhaps, those field lines bunch up in an elongated manner that is no longer attached to the antenna, but which seems to be moving away from it in a perpendicular direction. At every half-cycle of the oscillation, the direction of each successive bunch reverses the direction of its force field.

Because of the relatively compressed shape of the fields, they maintain their strength over a much more concentrated area than the spread-out static fields shown earlier.

To understand the behaviour of the fields, it is important to carefully consider the passage of time that can be seen in these plots. The arrows closest to the antenna represent the field at the moment of its creation, directly corresponding to the electric potential right now on the wire of the antenna. Because the electric and magnetic fields propagate at the speed of light, the arrows shown further away from the antenna represent what the wire was doing a moment ago. Each reversal of the direction of the electric potential happens twice in every cycle. Each set of bunched-up field lines pointing in the same direction is half of the wavelength apart – half of λ – from the adjacent set that points in the opposite direction. In terms of time, each set must have been created half of the period earlier than the one closer to the antenna.[103]

It is the combination of the passage of time and the field's propagation away from the antenna at the speed of light, and the acceleration and deceleration of the electrons in the antenna's wire that cause the field's lines of force to form the elongated, compressed sets that eventually become parallel to the wire, and which reverse their direction twice in every cycle.

Let's see what happens next, starting with Figure 7-iv. At time t=1/8, as the electrons start accelerating again, travelling in the opposite direction, down, the voltage between antenna's ends decreases, and the distribution of charges changes accordingly. The electric field direction follows the changes, as shown by the orange arrows closest to the wire. Those arrows are starting to turn clockwise on the left and anticlockwise to the right of the antenna. This commences the reversal of the direction of the field's force closest to the antenna. Those closest orange arrows, and

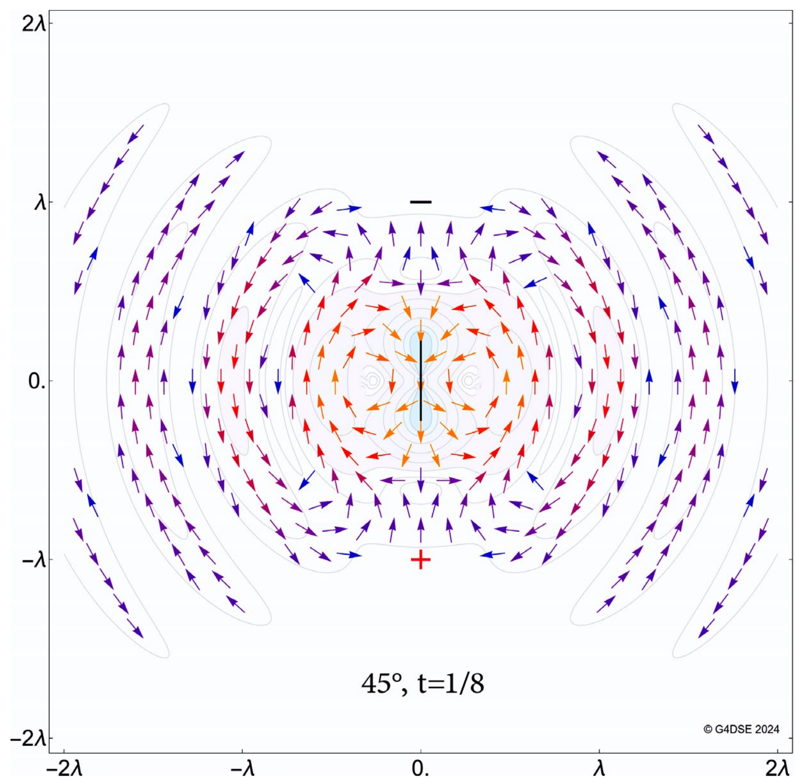

Figure 7-iv: Electric field surrounding the dipole at the 45° phase, 1/8th of a cycle from the start. Voltage is weakening. [Image by Peter Zollman, see page 375]

103 Recall that $period = 1/f$ and wavelength in metres $\lambda = 300/f$, where f is the frequency, in MHz, of the AC being fed to the antenna. For example, if feeding AC whose frequency is 7 MHz, the wavelength is about 42 m. The distances between one bunch of field lines and the one that follows it pointing in the opposite direction is about 21 m. Even though the speed of light is huge, at these frequencies the distances covered by the radiating field are surprisingly small in each half cycle. See 5.1.3 Wavelength and Frequency.

the orange arrows slightly further away, representing the field a few moments ago, appear like clockwise loops on left of the antenna, and anticlockwise on the right. In the three-dimensional reality, they would be more like donuts surrounding the wire, but the illustration shows a slice through them.

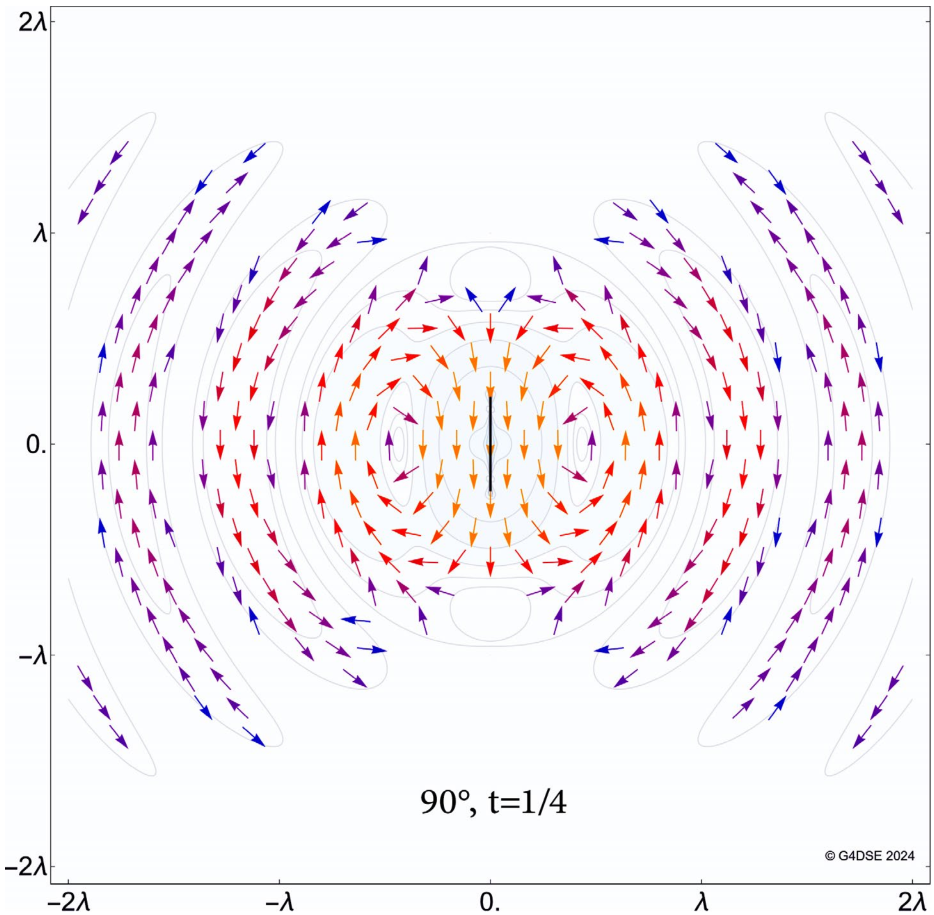

Figure 7-v: Electric field surrounding the dipole at the 90° phase, 1/4th of a cycle from start. Notice that the field lines closest to the antenna are no longer pointing to it. They are now parallel to the wire. [Image by Peter Zollman, see page 375]

Another eighth of the cycle later, shown in Figure 7-v, at time t=1/4, the voltage between antenna's ends is zero. The closest to the antenna orange arrows of the field's force no longer point to or from it. They are now *parallel* to it, closing a force field loop that begun half a cycle ago. This is a crucial moment in the formation of the wave. This set of field lines is no longer attached to the wire! By becoming parallel to it, it became free, and it will soon propagate away, in the perpendicular direction away from the antenna.

However, as the AC keeps on oscillating, electrons accelerate again, and the opposite voltage soon starts to build up between the ends of the antenna. The top is now becoming positive, and the bottom is now negative. At time t=3/8 electrons are

decelerating ahead of their next standstill. See Figure 7-vi on the right. Voltage is no longer zero, but not yet at its maximum between the antenna's ends. The orange field force arrows, closest to the wire, are turning, now anti-clockwise on the left, but clockwise to the right of the antenna. A new cycle of wave formation is well in progress.

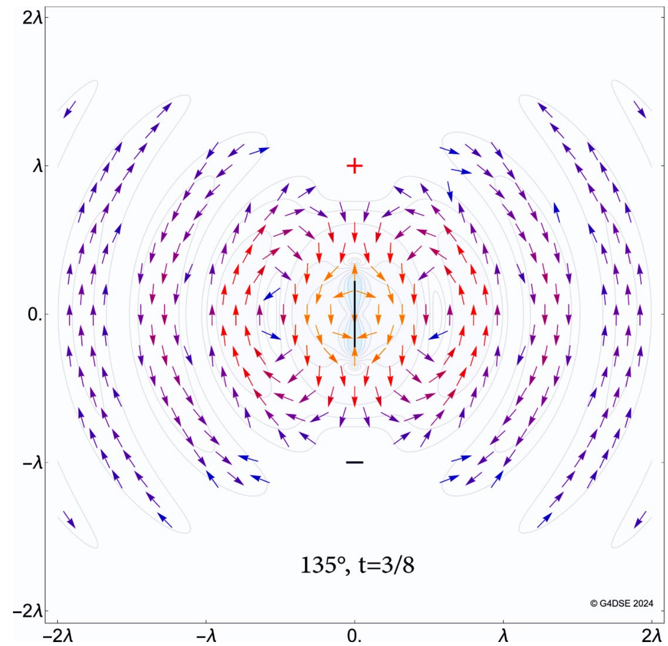

Figure 7-vi: Electric field surrounding the dipole at the 135° phase, 3/8th of a cycle from start. [Image by Peter Zollman, see page 375]

At time t=1/2, shown in Figure 7-vii below on the right, exactly half a cycle later than at the start at t=0 in Figure 7-iii, maximum voltage has been reached between the ends of the antenna again, except it is now the other way round: positive above, negative on the bottom. Electrons have once again reached their momentary standstill, and the force lines are pointing at right angles towards and away from the antenna. Half of the new loop is in place. Soon, electrons will accelerate upwards, and the arrows closest to the wire will turn up, and the field lines will bend. A quarter cycle from the start, at t=3/4, 270° phase (not shown) the voltage will be again at zero, and the new set will become parallel to and detached from the wire, while the previous one will have already propagated one wavelength away. The process will continue for as long as AC is being supplied to the antenna.

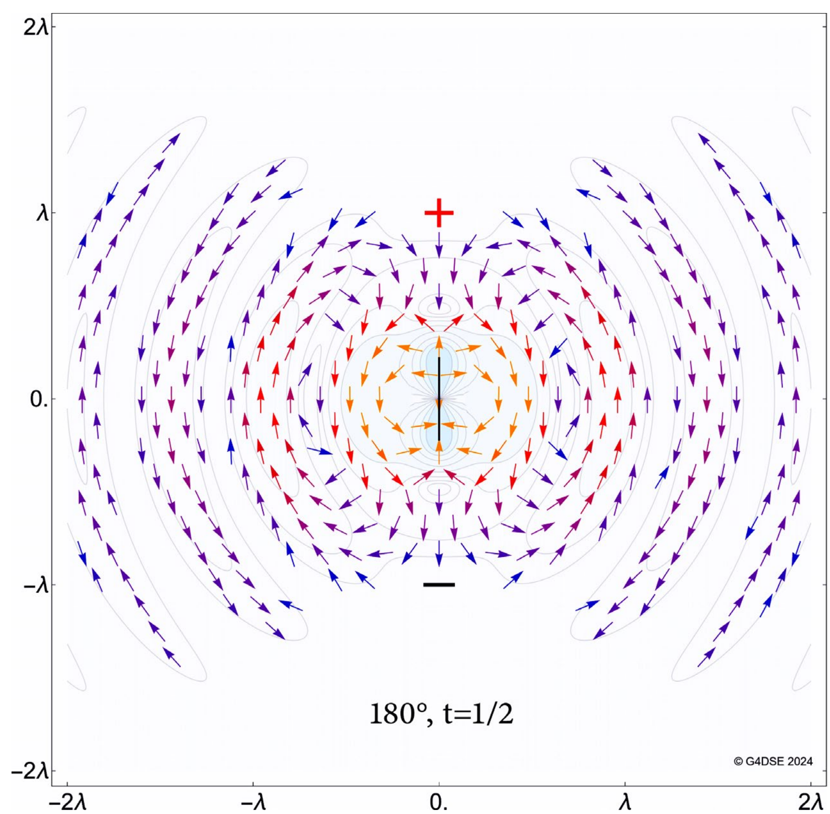

Figure 7-vii: Electric field surrounding the dipole at the 180° phase, 1/2 of a cycle from start. [Image by Peter Zollman, see page 375]

7.3.5 Propagating Electromagnetic Wave

To give a sense of distance, plots show a scale labelled in λ, the wavelength. For a typical half-wave dipole antenna used on the 40 m band, and not considering the effects of reflections from the ground, the fields up to about 20 m away from each side of the antenna are still being formed and remain attached to the wire. Those further than about 40 m away from the wire are mainly detached and propagating freely.

Far away from the antenna, the curvature of the field lines is no longer easy to notice, and the squashed sets appear as parallel, straight lines, travelling transverse to it, i.e., oscillating parallel but moving perpendicular to it.

A plot of the field lines at far distances from this antenna is shown in Figure 7-viii on the left. The distance is about 200 λ, or about 8 km away from the 40 m band antenna. Notice the very gentle curvature of the field that becomes straighter and more parallel the further it gets.

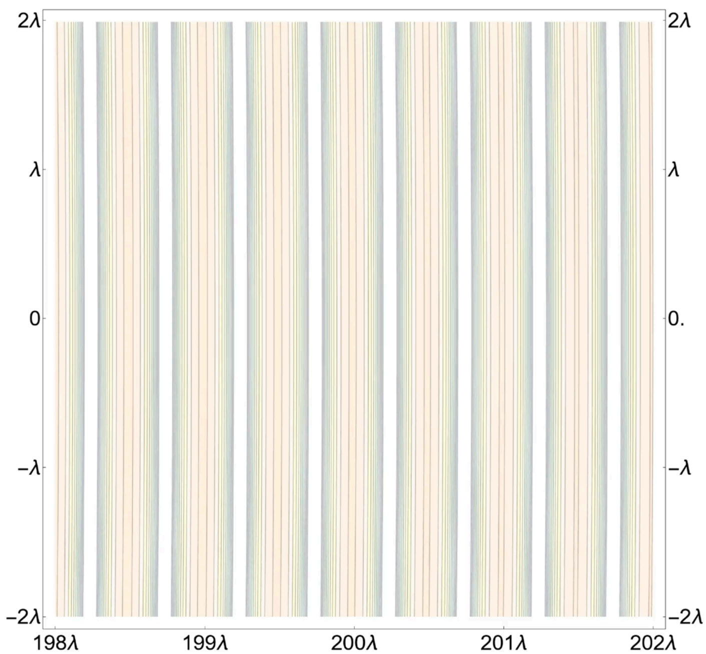

Figure 7-viii: Electric field strength (magnitude) far away from a half-wave dipole antenna. Orange is strongest, blue weaker, and white gaps show weakest field strength. [Image by Peter Zollman, see page 375]

Even though the explanation has focused on the radiating electric field, there is also a magnetic field involved. Although the electric and magnetic fields closest and touching the antenna are 90° out of step with each other, once they have detached from the antenna they propagate in a perfect unison. Their oscillations are perfectly synchronised with each other, and they are perpendicular to each other, as you have already seen in Figure 7-i further.

Figure 7-ix on the next page illustrates another way to see that the fields are in unison. This plot shows the magnetic field strengths surrounding the same antenna, and at the very same moment in time as shown in the plot of electrical field in Figure 7-iii, at time t=0 (0°). At that time the voltage between antenna's ends is at its

maximum, but the electrons just came to a momentary stop. That means there is no current flowing. That is the reason why the magnetic field becomes parallel to the wire and detaches from it.

Observe that closest to the antenna, the magnetic field is one quarter of the cycle, 90°, out of step with the electric field.

The magnetic field looks simpler and quite different from the electric field at distances very close to the wire, i.e., less than ½ λ. The electric field is more complex close to the wire because it contains both radiating and non-radiating components. However, only about half a cycle later, the two will align, because the non-radiating components of the electric field will have decayed.

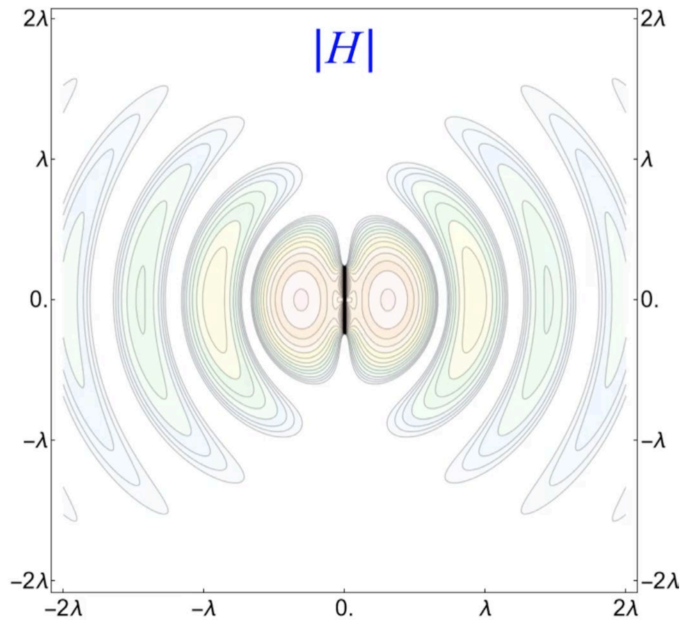

Figure 7-ix: Magnetic field strength (magnitude) surrounding an active half-wave dipole antenna, shown as the vertical black line in the centre. Plot shows the same phase of the cycle as in Figure 7-iii, with the maximum voltage between the ends of the dipole, and zero current. [Image by Peter Zollman, see page 375]

The already detached, propagating magnetic field lines, about λ away from the antenna, are identical[104] to the electric field lines. From that distance onwards, the two fields become perfectly synchronised.

Once in sync, these two fields are so closely related to each other that they are just called an ELECTROMAGNETIC WAVE. It is no longer necessary to distinguish between the electric and the magnetic counterparts. RADIO WAVE is the most commonly used name for the radiating EMFs that are used for radio communication.

As you feed AC energy to the antenna, the acceleration and deceleration of the electrons is replenished, and the radiation continues. When AC stops, the antenna stops radiating, and no more radio waves are being produced by it. However, the already radiated electromagnetic wave – that is already further away – will keep propagating even further, on its own. It has taken away some of the energy that was used to accelerate and decelerate the electrons, and it is carrying that energy through space by constantly varying the direction and strength of the force field at every point it passes.

The radio wave will match the sinusoidal AC that has created it, matching its frequency and period, and closely matching many of its other aspects, including its power.

104 The fields are 90° perpendicular to each other in terms of the direction of their oscillation in space, however, their strengths are perfectly synchronised, i.e., in phase with each other. The plot above only shows field strengths, not their spatial orientation, which was shown in the earlier Figure 7-i.

Most importantly, the radio wave will carry the information that has been impressed upon the AC by means of modulation, including speech, data, and any other signals you wanted to transmit. This is how we communicate using radio waves.

The radio wave never stops as it travels towards infinity. It does appear weaker as it spreads out covering an ever-expanding stretch of space.[105] However, the decrease of strength is gentle enough for the wave to be detectable far, far away. That is the reason why we can use radio to remotely control spacecraft on other planets, like Mars. That is why we can detect radio waves emitted by the farthest objects in our galaxy, and even further, in the universe.

It is also the reason why all radio transmissions that have ever been sent from our planet, Earth, including your radio calls, will eventually reach other planets, stars, and the edges of the known universe.[106]

7.4 Frequency

The number of times the fields complete a single, full oscillation, that is from the strongest in the first direction, through nothing, through the strongest but in the opposite direction, again through nothing, back to the strongest in the first direction, in *one second,* is known as the FREQUENCY of the electromagnetic wave. It is the same concept as the frequency of a sinusoid. See section 5.1 Sinusoidal Signals to understand the relationship between frequency and the wavelength and to be able to convert one into the other, especially for the commonly used radio bands, mentioned below.

Ranges of the commonly used amateur RADIO FREQUENCIES (RF) are often referred to as LF, MF, HF, VHF, and UHF. The names of the ITU RADIO BANDS that designate these ranges are shown in Table 7-A.[107] To see how those ranges relate to the amateur radio frequencies, see Table 25-C on page 343.

Table 7-A: ITU radio band names (subset: LF, MF, HF, VHF, UHF)

Abbreviation	**Designation**	**Frequency range**
LF	Low Frequency	30–300 kHz
MF	Medium Frequency	300 kHz–3 MHz
HF	High Frequency	3–30 MHz
VHF	Very High Frequency	30–300 MHz
UHF	Ultra High Frequency	300 MHz–3 GHz

105 This somewhat gentle weakening of a radio wave will be discussed, again, in section 16.4.1 Free Space Attenuation.

106 There are other theories in physic that explain electromagnetic radiation. The presented explanation relies on *classical electromagnetism* and on the *special theory of relativity.* An alternative interpretation is *quantum electrodynamics.* It explains how the energy is transferred from the antenna by energetic quantum particles known as *photons,* instead of relying on the concept of a wave or even a field. Fortunately, the two theories are consistent with each other, and even help explain each other.

107 This subset of the bands is most commonly used by radio amateurs. This is the set that needs to be known for the exam. The ITU, however, designate further bands below, like VLF, and above, like SHF. See the full table at en.wikipedia.org/wiki/Radio_spectrum.

You also need to know the term MICROWAVE FREQUENCY. It is the 1–300 GHz range, which starts in UHF and continues above it.[108]

7.5 Radio Spectrum

Spectrum is a word that describes how anything can be classified by its relative position to another thing. If you have seen a rainbow, you have seen a band of colours that represents the spectrum of visible light. Light is an electromagnetic wave. The colours in the rainbow are arranged by the frequency of the wave, with the lowest frequency represented by the red light and the highest by the violet[109]. The spectrum of visible light is part of the much wider ELECTROMAGNETIC SPECTRUM, shown in Figure 7-x. The RADIO SPECTRUM is also a part of the electromagnetic spectrum. However, radio wave frequencies are much lower than those of the electromagnetic waves of visible light.

The electromagnetic spectrum includes not only radio waves, but also other types of electromagnetic radiation, such as visible light and x-rays. An important distinction, especially for reasons of safety, is that the lower part of the electromagnetic spectrum, which includes visible light and everything with lower frequencies, including radio waves, is known as NON-IONISING RADIATION. Electromagnetic waves with frequencies much higher than visible light, such as some *ultraviolet,* all *x-rays* and *gamma waves,* are known as IONISING RADIATION. Ionising radiation, sometimes called nuclear radiation, is inherently dangerous. On the other hand, non-ionising radiation has proven to be safe if sensible precautions are taken, see section 19.8 Non-Ionising Radiation and Electromagnetic Field Safety.

Figure 7-x on the next page shows the entire electromagnetic spectrum, its frequencies and wavelengths.[110] Radio waves occupy a section of the spectrum from 3 kHz (3000 Hz) beyond the left edge, to 3000 GHz (3 000 000 000 000 Hz).[111]

108 Microwaves start in UHF, and span Super High Frequency (SHF), and Extremely High Frequency (EHF) bands. Your licence permits the use of some frequencies in the SHF and EHF bands. There is one more ITU band above microwaves, below infrared, called Tremendously High Frequency (THF).

109 Electromagnetic waves that we see as the visible light have frequencies between 400 THz (red light) and 790 THz (violet light). The metric prefix T, tera, means 1 000 000 000 000, or 10^{12}. In other words, 1 THz (one terahertz) is 1000 GHz, or 1 000 000 MHz.

110 The frequencies and wavelengths, like all very large or small quantities, can be conveniently described using the *power-of-10* notation, shown in this figure. The *power,* that is the small number shown above the 10, for example the number ^{3} in 10^3, represents how many zeros there should be *after* the 1 if this number was written out in full. $10^1 = 10$, $10^3 = 1000$, $10^6 = 1000000$. If the power is a negative number, it works similarly. It is used for decimal numbers smaller than 1 in which the power denotes the number of zeros in *front* of 1. For example, $10^{-1} = 0.1$, $10^{-3} = 0.001$, $10^{-6} = 0.000001$. For completeness, $10^0 = 1$, because the power of ^{0} of *any* number is always 1. Technically, power represents the act of multiplying the number by itself as many times as the power, if it is positive. If negative, the result is then divided into 1. This notation is also used in Table 3-B: Selected SI metric prefixes on page 15. It prevents mistakes in having to carefully count the many zeros in long numbers.

111 3000 GHz (gigahertz) = 3 THz (terahertz). See also footnote 109 for an explanation of a *terahertz.*

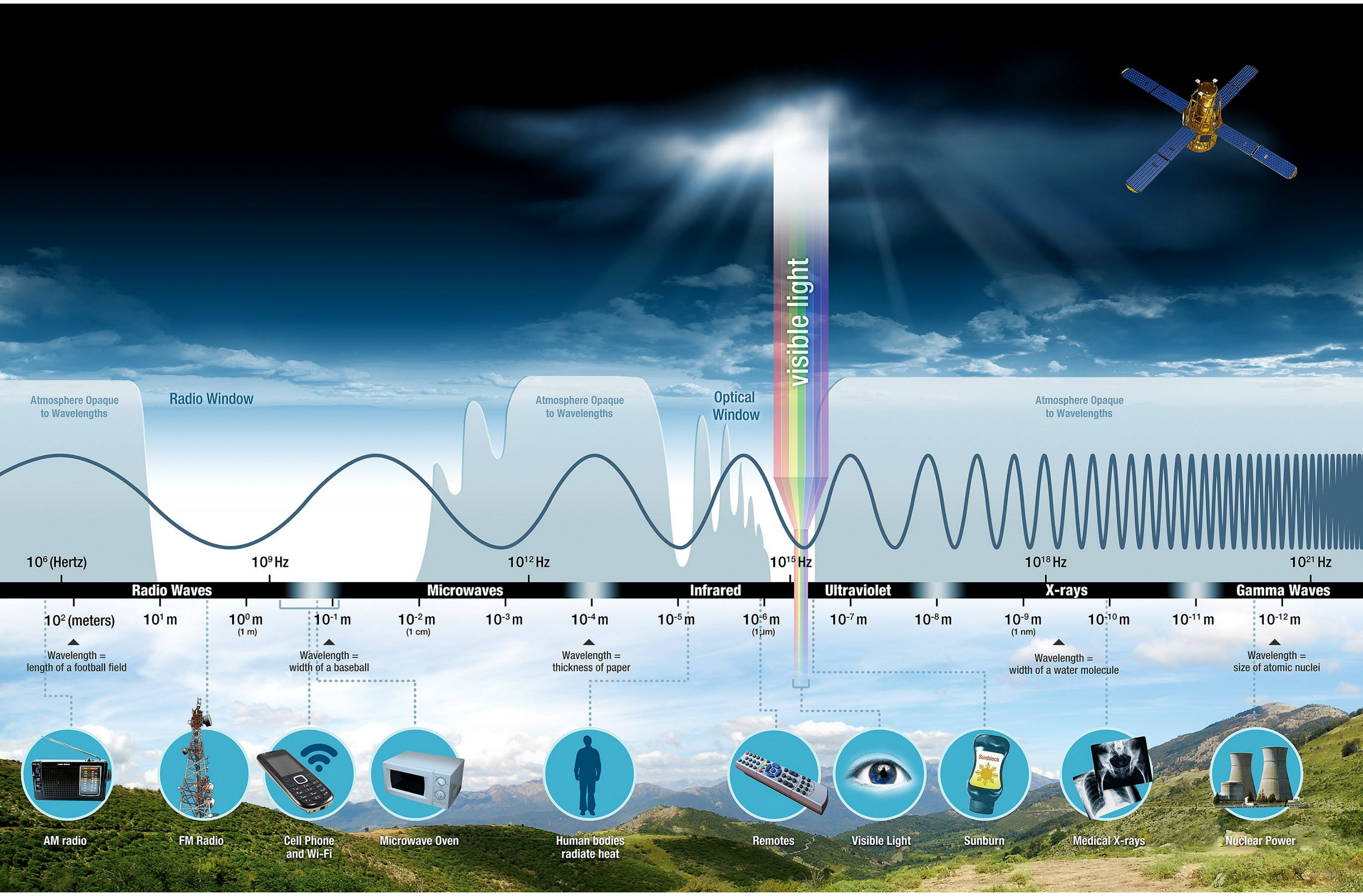

Figure 7-x: The electromagnetic spectrum. [Image by NASA, see page 375]

Please note that the exam syllabus focuses only on the parts of the spectrum listed in Table 25-C on page 343, and not the entire spectrum shown in Figure 7-x.

7.6 Electric Field

An ELECTRIC FIELD describes forces resulting from electric charges in every point of space. The ELECTRIC FIELD STRENGTH is measured in volts/metre (V/m). It is inversely proportional to the distance from the source. At *twice* the distance the field strength is *halved*.[112]

Electric field strength may also be expressed as the POWER DENSITY in watt/metre^2 (W/m^2). Power density is proportional to the inverse of the square of the distance from the source. At *twice* the distance, the power density is only a *quarter* of what it was at the source. See footnote 30 for more information about squares and the inverse square law.

An electric field is created by a difference in electric potential, such as when there are more electrons in one place than in another. In radio, this usually means that a voltage between the ends of an antenna causes an electric field to form. An electric field can be also created by a changing magnetic field. Conversely, a changing electric field creates a magnetic field.

7.7 Magnetic Field

In addition to an electric field, every conductor carrying a current, not only AC but even DC, has a MAGNETIC FIELD around it caused by the flow of the electrons. A steady current creates a static, that is, a non-changing magnetic field around the conductor. AC flowing through a conductor creates not only an oscillating magnetic field but also an oscillating electric field. This process is explained in the earlier, optional section 7.3 Fields and Wave Formation.

The MAGNETIC FIELD STRENGTH is measured in amperes/metre (A/m) and is inversely proportional to the distance from the source. At twice the distance the field strength is halved.[113]

112 This important law applies to distances measured well away from the antenna, at least a few wavelengths away from it, in the *far field* of the antenna. See also 15.2 Near and Far Antenna Fields.

113 As with the electric field, this law primarily applies in the far field of the antenna.

7.8 Polarisation

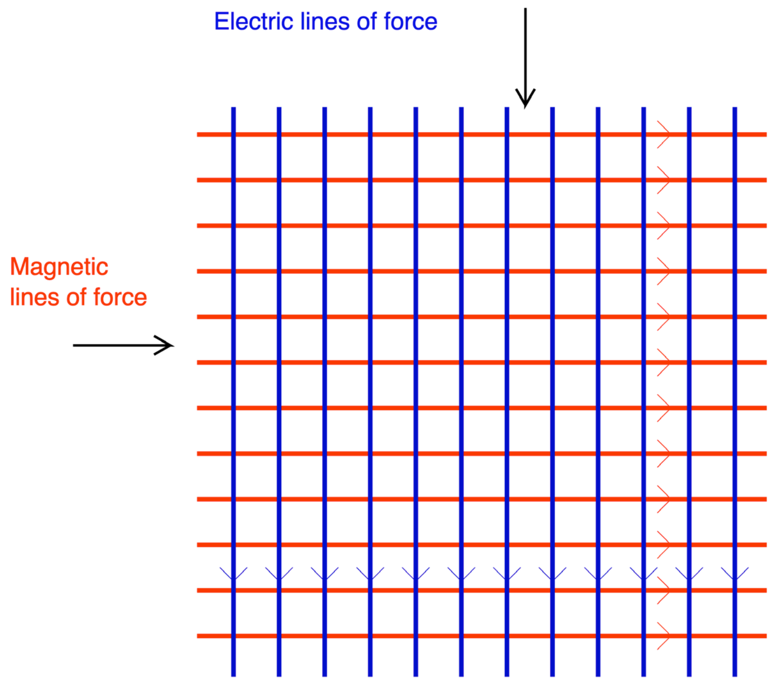

Figure 7-xi: Magnetic lines of force perpendicular to electric lines of force in a vertically polarised electromagnetic field. [EI9ILB]

The electric (E) field determines the POLARISATION of the electromagnetic wave. An electromagnetic wave is said to be polarised in the direction of the electric lines of force relative to the surface of the earth. In Figure 7-xi the wave is vertically polarised.

Polarisation is determined by the transmitting antenna. Horizontal antennas transmit horizontally polarised waves and vertical ones vertically polarised waves. Polarisation of waves can be altered when it refracts or reflects from other surfaces, including the atmospheric layers. Waves refracted by the ionosphere are no longer horizontally nor vertically polarised.[114]

114 Waves refracted from the ionosphere become *elliptically* polarised, i.e., they have aspects of both the horizontal and the vertical polarisation.

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8 Resonant Circuits and Components

THREE EXAM QUESTIONS · SECTION A4

This chapter discusses electronic components that are used to make resonant circuits. These circuits are of great importance to radio because they are used to generate and process the AC that represents radio signals.

To understand how resonant circuits work you first must understand the concept of reactance. While it is like resistance, it has important differences. Reactance depends on the frequency of the AC. It also impacts the phase difference between the voltage and the current of an AC circuit. Understanding this phase difference is critically important when selecting or designing an antenna and a transmission line to match the radio. They are discussed in Chapters 14 and 15.

The next two subsections introduce inductors and capacitors, the two key building blocks of resonant circuits. Make sure to understand their inductive reactance and capacitive reactance as you study them, as it will help you understand impedance and resonance. You will also learn about the most important resonant circuits: series and parallel tuned circuits, which have many uses, especially as the building blocks of filters and oscillators.

You should have studied the previous sections of this guide before you embark on this one. The concepts introduced here rely on an understanding of electronic principles, AC, and both sinusoidal and non-sinusoidal signals.

8.1 Resonant Components: Inductors

An INDUCTOR is a passive electrical component that stores energy in a magnetic field and consists of a wire wound into a COIL, after which it takes its common name. It is also sometimes called a CHOKE because of its effect on AC, especially at higher frequencies.

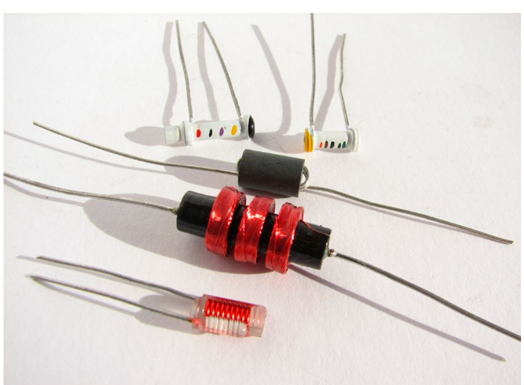


Figure 8-i: Inductors. [Images by: Windell Oskay (left), Jacques (right), see page 375]

The electronic symbol for an inductor is shown in Figure 8-ii.

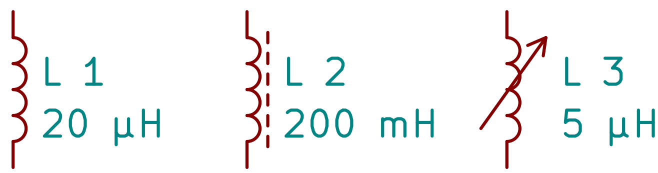


Figure 8-ii: Symbols for inductors, from left: fixed inductor, inductor with a ferrite core, and a variable inductor. [EI9ILB]

Any wire carrying a current is surrounded by a magnetic field. Winding the wire into a coil strengthens this field. When the current through a coil changes, the magnetic field opposes the change. This opposition to change is called inductive reactance and it will be explained in section 8.1.3. How much inductive reactance will there be? That depends on the inductance of the coil. INDUCTANCE is an important characteristic of all inductors, just like resistance characterises resistors. Like resistors, tolerance is also a property of inductors, allowing for its stated inductance to vary within a narrow, specified range, to allow for manufacturing variability. Because inductance used for radio purposes needs to be precise, variable and adjustable inductors are used, allowing for a fine tuning.

Inductance increases with the number of turns of the wire and the diameter of the coil. It decreases if the spacing between the turns is increased. Adding a conducting CORE changes inductance depending on the permeability of the core material. FERRITE CORES increase inductance. BRASS CORES decrease inductance.

The unit of inductance is the HENRY (H) but as this is a large unit, the milli– and microhenry (mH, µH) are more commonly used.[115] The dimension symbol of inductance, which you will see in formulae, is the letter L.

In electronic circuits, inductors are mainly used where the current is alternating – such as in AF and RF circuits. However, the resistance to the change of the magnetic field will also affect a direct current (DC), i.e., a non-AC circuit during the switch-on phase. If an inductor is connected to a DC power supply, the sudden increase of current in the inductor is initially resisted, but when the current becomes stable, the inductor no longer resists the DC.

8.1.1 Back Electromotive Force

As current enters an inductor it produces a BACK ELECTROMOTIVE FORCE, also known as BACK EMF, counter-electromotive force, counter emf. It opposes the very current that is trying to pass through the inductor. When DC passes through an inductor, this opposition only lasts during the initial surge, and not when the current stabilises. However, when AC passes through an inductor, the back emf is continuous,

115 See Table 3-B: Selected SI metric prefixes on page 15 for the list of all the metric prefixes used in this guide, including milli and micro.

because the current is constantly changing its rate and the direction of flow through the inductor.

This back emf will appear as a voltage across the coil's winding. The polarity of the voltage tries to oppose the change, as if it were trying to keep the current constant.[116]

8.1.2 Inductors in Series and Parallel

When connecting inductors in series or parallel, their EQUIVALENT INDUCTANCE can be calculated in the same way as the method for finding equivalent resistance of series and parallel connected resistors. Please refer to sections 4.2.2 and 4.2.3 for detailed instructions how to calculate it, replacing R with L in the formulae. The remainder of this subsection summarises those instructions.

The equivalent value of inductors connected in *series*, L_{eq}, is the *sum* of the inductances of all the inductors:

$$L_{eq} = L1 + L2 + L3 \dots$$

Just like resistors, inductors in series increase the equivalent value: it is always greater than that of the highest series connected inductance.

Again, just like with resistors, the equivalent value, L_{eq}, of inductors connected in *parallel* is the *inverse*[117] of the sum of the *inversed* inductances. This can be obtained from this formula:

$$\frac{1}{L_{eq}} = \frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} \dots$$

The result still needs to be inverted. To find out L_{eq}, divide 1 by the result from the above. In other words:

$$L_{eq} = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} \dots}$$

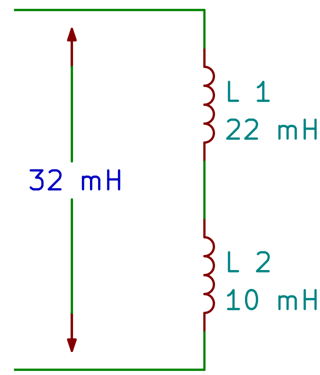


Figure 8-iii: Two inductors, 22 mH and 10 mH, connected in series. Equivalent inductance is 32 mH. [EI9ILB]

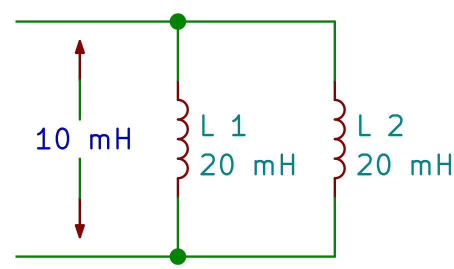


Figure 8-iv: Two inductors, each 20 mH, connected in parallel. Equivalent inductance is 10 mH. [EI9ILB]

116 The cause of the back emf is magnetic induction. It was independently discovered by Michael Faraday, an English physicist, in 1831, and by Joseph Henry, an American physicist, in 1832, after whom the unit of inductance is named. Magnetic induction is described by Faraday's law of induction, a law of physics. It was later reformulated into one of the four famous Maxwell equations which govern all electromagnetism including the nature of radio waves and how antennas work.

117 *Inverse* of a number means *1 divided by that number.* For example, inverse of 2 is 1/2 which is ½ which is 0.5. Inverse of 10 would be 1/10 which is 0.1. Inverse of 0.5 is 1/0.5 which is 2. Inverse of 0.1 is 1/0.1 which is 10.

Inductors in parallel reduce the equivalent value. It is always less than that of the smallest parallel connected inductance.

If you need to calculate the equivalent inductance of a combination of inductors connected in parallel and in series follow the same procedure as for resistors, see section 4.2.4.

8.1.3 Inductive Reactance

An inductor opposes any changes to the current. This opposition is called INDUCTIVE REACTANCE. Like resistance, it can be calculated from the ratio of voltage rms[118] to the current rms passing through an inductor. Its unit is ohm (Ω). Its dimension symbol is X_L which you can see in these formulae:

$$X_L = \frac{V}{I}$$

$$I = \frac{V}{X_L}$$

$$V = I\ X_L$$

You may have noticed that those formulae would look exactly like Ohm's law if we replaced inductance X_L with resistance R. However, there is a major difference. Inductive reactance depends on the frequency of the alternating current that is passing through the inductor.

Please note, inductance stays the same, no matter the frequency, because it is a property of the inductor's construction. However, the inductive reactance that describes that opposing force increases with frequency: the higher the frequency the higher the inductive reactance of a coil. The following formula shows how to calculate inductive reactance X_L, if you know the inductance L of the inductor and the frequency f of the current:

$$X_L = 2\pi f L$$

Pi or π can be rounded to 3.14 for accurate enough calculations for the *purposes of the exam*. In line with how mathematical formulas are written, the multiplication symbol does not need to be shown – you will no longer see it in the remaining formulae of this guide. The meaning of this formula is the same as if we multiplied all the values on the right-hand side.: $X_L = 2 \times \pi \times f \times L$

For example, the inductive reactance of a 1 μH inductor at 2 MHz frequency is 13 Ω – rounded up from 12.56:

$$X_L = 2 \times 3.14 \times 2\ 000\ 000 \times 0.000\ 001 = 13\ \Omega$$

118 Voltage *rms* is covered in section 5.1.5 rms, Effective Voltage, Peak-to-Peak Voltage, Power. It is necessary to use rms values in these formulae because, unlike with DC, in AC the value of voltage and current changes *all* the time. However, the *rms* value of a sinusoid, including AC, remains the same. It is a convenient way to describe voltage and current of AC.

There is another important difference between inductive reactance and resistance. It is related to the phase between the current and the voltage (phase was explained in section 5.3). The current and the voltage flowing through a resistor remain in phase. However, if an AC voltage is applied to an inductor, the back emf that the inductor generates causes the current to LAG voltage by 90°.

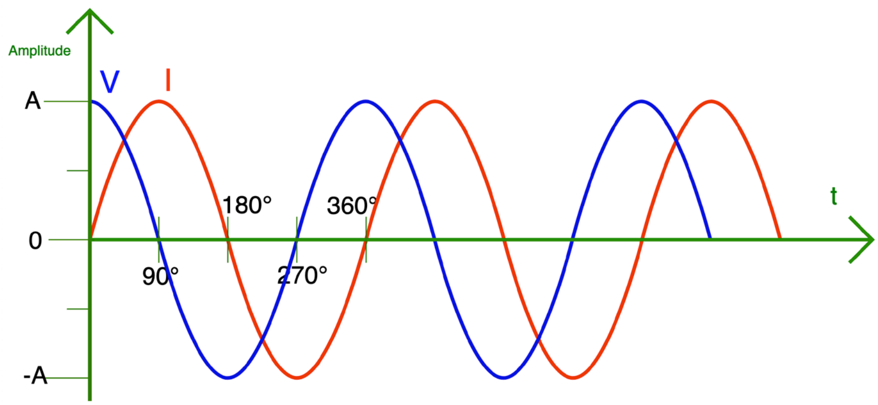


Figure 8-v: Alternating current lags voltage by 90° in an inductor. [EI9ILB]

You can think of the lag as a delay. In this case, the amplitude of the current does what the voltage did but a little later.[119] The voltage LEADS current in an inductor.

8.2 Resonant Components: Capacitors

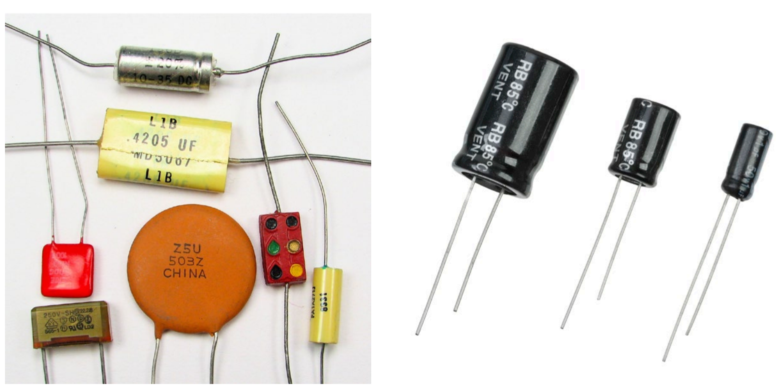


Figure 8-vi: Different types of capacitors.
[Images by (from left): Windell Oskay, Evan-Amos, see page 375]

119 90° later for a sinusoid means ¼ of the cycle later, because the cycle is represented by 360°. Recall that the duration of a cycle is called a *period,* and it is the inverse of *frequency.* For example, mains voltage is 50 Hz. Its period lasts 1/50 s = 20 ms, or 0.02 s. That means the current will *lag* voltage by 5 ms. Current will reach the peak value 5 ms later than voltage; current will reach zero 5 ms after voltage; current will reach minimum value 5 ms later than voltage, and so on.

A CAPACITOR is a passive electrical component that stores electrical energy in an electric field – as opposed to an inductor, which stored energy in a magnetic field. The most common electronic symbols for capacitors are shown in Figure 8-vii.

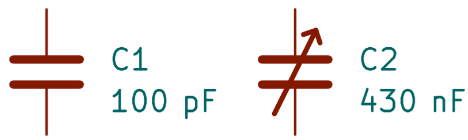


Figure 8-vii: Symbols for capacitors, fixed (left), variable (right).

A capacitor is made from two metal plates, or from one metal plate and a conducting gel, close to each other but not touching, separated by a dielectric such as the air. It will store an electric charge between its two conductors. This ability of a capacitor is known as CAPACITANCE.

The unit of capacitance is the FARAD (F) but as this is a very large unit the micro–, nano–, and picofarad (μF, nF, pF) are used often.[120] The dimension symbol of capacitance that you will see in formulae is the letter C. Capacitance depends on:

- the area of the plates: the larger the plates, the higher the capacitance
- the distance between them: the closer they are, the higher the capacitance
- the DIELECTRIC CONSTANT of the material between them: materials with a higher dielectric constant increase capacitance.

It is useful to have capacitors whose capacitance can be adjusted because it makes it possible to build adjustable resonant circuits. VARIABLE CAPACITORS have many uses, notably for tuning, see Figure 8-viii.

Since capacitance depends on the area and the distance between the metal plates, a mechanical variable capacitor is often used for this purpose.

Capacitors have a maximum working voltage that they can support. They also have a tolerance, expressed as a percentage, such as ±1%, ±5%, … that allows for their capacitance to vary from the specified value for manufacturing reasons.

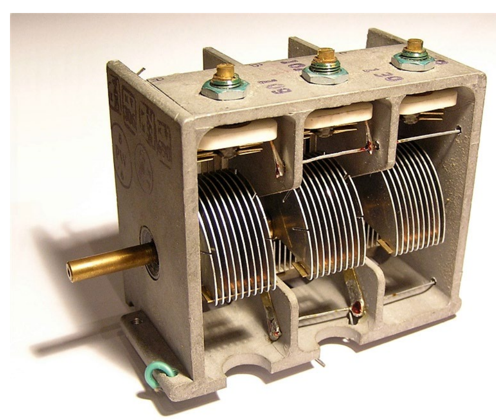


Figure 8-viii: Variable capacitor, used for tuning. [Image by Mumin 123, see page 375]

120 See Table 3-B: Selected SI metric prefixes on page 15 for the list of all the metric prefixes used in this guide, including micro, nano, and pico.

8.2.1 Dielectrics

A DIELECTRIC is an electrical insulator, see 3.3.2 Conductivity, that has the additional property that under the influence of an electric field the positive electric charges, such as protons, move away from the negative ones, such as electrons, and remain in that separated position. As a result, the dielectric material retains a static electric field for a long time.[121] This is how a capacitor stores electric energy between its metal plates.[122]

Dielectrics have other uses in radio technology. They are essential to the design of transmission lines, see Chapter 14 Transmission Lines. The common dielectrics are:

- AIR: used for variable capacitors with a set of fixed and moving plates allowing the effective plate area to vary, as shown in Figure 8-viii
- PAPER: layers of metal foil separated by paper
- PLASTIC: convenient, especially in flexible coaxial transmission lines, see 14.6 Coaxial Line
- MICA, SILVERED MICA, CERAMIC
- METAL OXIDE: offer large capacitance in electrolytic capacitors, in which the gel or fluid electrolyte fulfils the role of one of the plates.[123]

8.2.2 Behaviour of Capacitors in AC and DC

When DC is applied to a capacitor there is an initial surge of current as the capacitor charges, and then, when charged, no further current flows. This happens very quickly. As a result, once charged, a capacitor blocks DC from flowing. In a practical capacitor there will be, however, some small amount of current flowing through the dielectric. This is known as the LEAKAGE CURRENT.

121 In ideal conditions, a capacitor can retain its charge for months or even years. This is one of the reasons why when working with electronic equipment that contains high-capacity capacitors care is needed to ensure they are discharged before being touched. Some equipment includes high-resistance resistors to ensure that capacitors always discharge, albeit slowly, to avoid such issues. See 19 Safety.

122 Interestingly, capacitors have not replaced batteries. Capacitors can hold charge for a long time, they charge very quickly, and they last a very long time, sustaining significantly more charge-discharge cycles than a battery. Unfortunately, they have small capacities in comparison to batteries. Supercapacitors may change that in the future, see en.wikipedia.org/wiki/Supercapacitor

123 Air and vacuum capacitors are used for tuning circuits. As plate spacing determines working voltage, capacitors used for antenna tuning units require large spacing, up to 1 cm, and can be physically large. Paper capacitors are also large and can support high working voltages. Plastics support high working voltages, too, but some, like polythene, polypropylene, and mylar can introduce losses when used in HF applications. Polystyrene and PTFE are less lossy at HF. Mica and ceramics support lower capacitance values, but they are stable and suitable for HF. There is also large capacitance hi-k ceramic, but not suitable for RF purposes. Electrolytic capacitors have only one metal plate. They contain electrolyte, which is a conducting liquid or a gel, that functions as one of the plates, the cathode. The other one, the anode, is a metal plate, on which a thin layer of a dielectric metal oxide has been formed chemically. They are polarised: they have a positive and a negative terminal. The get easily damaged if polarity is reversed or with more voltage than they were designed for. The electrolyte can dry up, causing failures. Figure 8-vi on the right shows electrolytic capacitors.

Unlike DC, AC can pass through a capacitor. This is possible because as soon as the direction of the current changes, the capacitor will discharge, initially even aiding the flow of the current with its stored charge, before rapidly being charged again, however with the opposing voltage. The higher the frequency of AC, the more easily the capacitor will allow it to be passed.

This behaviour is almost exactly the opposite to that of an inductor, which, as explained in section 8.1.3 above, passes DC easily but opposes the flow of AC as the frequency increases. This will be further discussed in 8.2.4 Capacitive Reactance.

8.2.3 Capacitors in Series and Parallel

When connecting capacitors in series or parallel, their EQUIVALENT CAPACITANCE can be calculated in the opposite way to the method for finding equivalent resistance of series and parallel connected resistors – and in the opposite way to finding equivalent inductance of series and parallel connected inductors. Simply replace R in those formulas with C (capacitance) and bear in mind these differences:

- series connected capacitors use the method described for *parallel* connected resistors, see 4.2.2, which is also the same as for parallel connected inductors, see 8.1.2,
- parallel connected capacitors use the method of *series* connected resistors, see 4.2.3, which is the same as for series connected inductors.

The equivalent value of capacitors connected in series, C_{eq}, is the *inverse*[124] of the sum of the *inversed* capacitances. This can be obtained from this formula:

$$\frac{1}{C_{eq}} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} \dots$$

The result still needs to be inverted. To find out C_{eq}, divide 1 by the result from the above:

$$C_{eq} = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} \dots}$$

Capacitors in series reduce the equivalent value: it is always less than that of the smallest series connected capacitance.

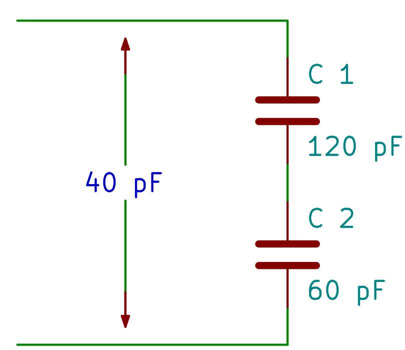


Figure 8-ix: Two capacitors, 120 pF and 60 pF, connected in series. Equivalent capacitance is 40 pF. [EI9ILB]

124 For an explanation of *inverse*, see footnote 117 on page 90.

The equivalent capacitance of capacitors connected in parallel, C_{eq}, is the *sum* of the capacitances of all the capacitors:

$$C_{eq} = C1 + C2 + C3 \dots$$

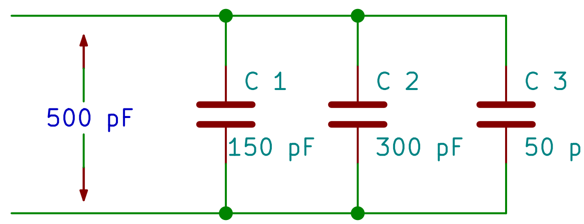


Figure 8-x: Three capacitors connected in parallel: 150 pF, 300 pF, and 50 pF. Equivalent capacitance is 500 pF. [EI9ILB]

Capacitors connected in parallel increase the equivalent value: it is always greater than that of the largest parallel connected capacitance.

To calculate the equivalent capacitance of a combination of capacitors connected in parallel and in series, follow the procedure for the resistors, see section 4.2.4.

8.2.4 Capacitive Reactance

Just like the inductive reactance, caused by the inductance of inductors, opposes AC (see 8.1.3 above), capacitors do something similar. Their capacitance causes CAPACITIVE REACTANCE which is also an opposition to the flow of AC. Capacitive reactance also depends on the frequency of the AC. However, unlike the inductive reactance, capacitive reactance *decreases* as the frequency increases. Capacitors do not allow DC [125] to pass at all as soon as they have charged.

Like inductive reactance and resistance, capacitive reactance can be calculated from the ratio of voltage rms to the current rms passing through a capacitor.[126] Its unit is ohm (Ω). Its dimension symbol is X_C which you can see in these formulae:

$$X_C = \frac{V}{I}$$

$$I = \frac{V}{X_C}$$

$$V = IX_C$$

Capacitance stays the same, no matter the frequencybecause it is a property of the capacitor's construction.[127] However, the capacitive reactance that describes that opposing force decreases with the frequency: the higher the frequency the lower the capacitive reactance of a capacitor. The following formula shows how to calculate

125 DC can be also thought of as AC with the frequency of zero Hz, that is, a never changing current. Capacitors provide infinite opposition to DC and that opposition weakens until there would be none as the frequency increases towards infinity. Inductors are the opposite. They do not oppose DC at all – there is no reactance for DC, but it grows towards infinite opposition as the frequency increases.

126 Voltage rms was explained in section 5.1.5 rms, Effective Voltage, Peak-to-Peak Voltage, Power. It is necessary to use rms values in these formulae because, unlike with DC, in AC the value of voltage and current changes *all* the time. However, the rms value of a sinusoid, including AC, remains the same. It is a convenient way to describe voltage and current of AC.

127 Capacitance does not depend on the frequency up to the design limit of the capacitor. Some dielectric materials can be lossy at RF and should not be used in such circuits. See 8.2.1 8.2.1 Dielectrics.

capacitive reactance X_C if you know the capacitance C of the capacitor and the frequency f of the current. The value of pi (π) can be rounded to 3.14.

$$X_C = \frac{1}{2\pi f C}$$

For example, the capacitive reactance of a 1 nF capacitor at 2 MHz frequency is 79 Ω (rounded):

$$X_C = \frac{1}{2 \times 3.14 \times 2\,000\,000 \times 0.000\,000\,001} = \frac{1}{0.0125} = 79\ \Omega$$

The other difference between capacitive reactance and resistance is related to the phase between the current and the voltage (phase was explained in section 5.3). Recall that the current and the voltage flowing through a resistor remain in phase. If AC voltage is applied to a perfect (pure) capacitor, the effect of the discharge of the capacitor aiding the current when it changes direction causes the current to LEAD voltage by 90°. This is exactly the opposite to what inductors do. An inductor causes the current to lag (not lead) the voltage.

Another way to think of the action of a capacitor is that it is opposing the increase of the voltage as it charges, while the current is flowing into the capacitor. In that sense the voltage LAGS the current, or the current LEADS the voltage.

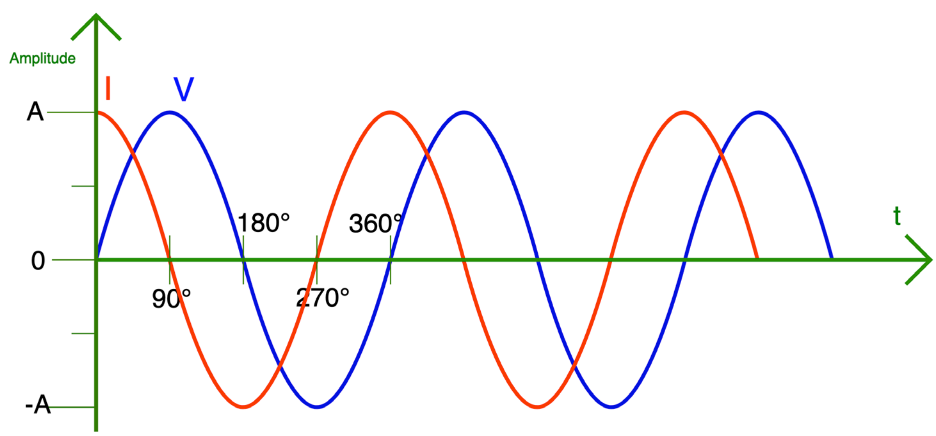


Figure 8-xi: Alternating current leads voltage by 90° in a capacitor. [EI9ILB]

You can think of the lead as being *ahead*. In this case, the amplitude of the current is doing what the voltage does but ahead of it.[128]

There is a symmetry between the behaviour of inductors and capacitors: they are similar but also the opposites of each other. The way they lead or lag in terms of the phases of the current and the voltage is opposite. The way their reactance changes as the frequency increases is also opposite. Even the way their equivalent values are calculated are opposite of the other component. This symmetry is very useful. By

128 See also footnote 119 on page 92.

combining capacitors and inductors in an AC circuit we can finely tune one to the other, achieving the desired behaviour from an antenna, transmission line, or a transceiver.

8.3 Reactance, Resonance, and Impedance

8.3.1 Reactance

As discussed above, AC will be opposed by inductors and by capacitors. That opposition is known as REACTANCE. It is measured in the unit of ohm, Ω.

- Inductive reactance X_L increases as the frequency increases.
- Capacitive reactance X_C decreases as the frequency increases.

The total reactance of a component, such as an antenna, or a circuit, is denoted by dimension symbol X. It is calculated by subtracting capacitive reactance from inductive reactance of that circuit.

$$X = X_L - X_C$$

If there is more inductive reactance than capacitive, the result is a positive number. Such a circuit, for example an antenna, is known to be INDUCTIVE. On the other hand, if there is more capacitive reactance the result is a negative number.[129] That circuit is known to be CAPACITIVE.

For example, for a circuit that has 13 Ω inductive reactance and 79 Ω capacitive reactance on a given frequency,[130] such as 2 MHz, the total reactance is −66 Ω.

$$X = 13 - 79 = -66\,\Omega$$

Because the result is a negative number, this circuit is capacitive. You could also ignore the minus sign and just say that it has a capacitive reactance of 66 Ω.

8.3.2 Resonance

What happens if inductive reactance is equal to capacitive reactance of a circuit comprised of an inductor and a capacitor, connected in series, on a given frequency? The total reactance would be zero. Such a circuit is known to be RESONANT on that frequency.[131] It is neither inductive nor capacitive on that frequency, although it would

129 Recognising that a negative value of reactance is capacitive while a positive value is inductive will be useful when you work with antennas, and it will help you read results from meters and analysers. It is also important in other calculations related to impedance, which, however, are *not* part of the exam.

130 This could be the circuit consisting of a 1 μH inductor connected in series with a 1 nF capacitor. Recall those are the same components whose reactance on the 2 MHz frequency was calculated in the previous two subsections, see 8.1.3 and 8.2.4.

131 There are several definitions of resonance. This guide offers the definition widely used in radio theory, i.e., a resonant circuit is one without reactance.

have some resistance.[132] These types of circuits are known as LC CIRCUITS. They will be discussed in section 8.4.1.

Resonance is an important property of many radio-related circuits and components, including antennas, transmission lines, transceiver outputs, and other station equipment. It is useful to know the resonant frequency of such circuits.

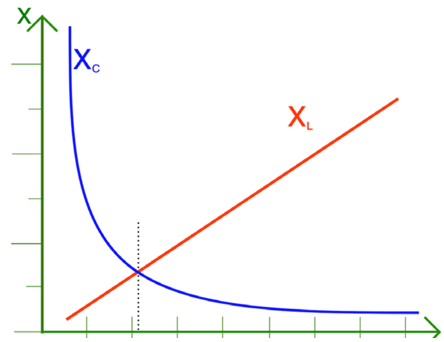


Figure 8-xii: Resonant frequency f when $X_L = X_C$ [EI9ILB]

Since both types of reactance depend on the frequency, one increasing and the other decreasing with the frequency, it is possible to find a frequency when both become equal and cancel each other out. Figure 8-xii shows the intersection between the decreasing capacitive reactance and the increasing inductive reactance of a circuit. That intersection represents the frequency at which those two cancel each other out and the circuit becomes resonant on that frequency.

A simple circuit comprised of a fixed-value capacitor and an inductor has one frequency on which it becomes resonant. It is known as its RESONANT FREQUENCY.

The formulae for inductive and capacitive reactance from sections 8.1.3 and 8.2.4 let us calculate reactance X_L and X_C for a given frequency f from inductance L and capacitance C. These two formulas can be combined to obtain a new formula to find the resonant frequency f_{res}. You do not need to memorise this formula for the purposes of the exam. However, you need to be aware that the resonant frequency depends on both the inductance and the capacitance of a circuit.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

For example, what would be the resonant frequency f_{res} of the example circuit consisting of a 1 µH inductor connected in series with a 1 nF capacitor?[133]

$$f_{res} = \frac{1}{2 \times 3.14 \times \sqrt{0.000\,001 \times 0.000\,000\,001}} = \frac{1}{0.000000198591037} =$$

$$= 5035474 \text{ Hz} = 5.035 \text{ MHz}$$

This circuit is resonant on approximately 5.035 MHz. This means its reactance on this frequency is zero ohm. You could verify this result using the formulae for inductive and capacitive reactance of the 1 µH and 1 nF components. You would find that they have an equal reactance of 32 Ω each on the 5.035 MHz frequency.

132 If it were possible to design a circuit that had no resistance, resonance could be achieved that way too, because, technically, for a circuit to be resonant its *impedance* needs to be zero. As you will learn in the next subsection, impedance combines reactance with resistance. However, such a theoretical circuit would not be very useful, because it would be resonant on all frequencies, rather than those of interest to us. In practice, all circuits always have some resistance, and resonance is achieved by reducing reactance to zero.

133 You will *not* be required to calculate it at the exam, but you are required to understand it.

If you understand how resonance represents a balance between inductive and capacitive reactance, you will understand how easy it is to adjust the resonant frequency of a circuit by adjusting its inductance and its capacitance. This is the fundamental principle of Antenna Tuning Units (ATUs). By using variable capacitors and variable inductors[134] the impedance of the transmission line and the antenna is adjusted to match the impedance of the signal source. Matching the impedances permits the maximum transfer of power to and from the antenna, and it minimises losses in the cables. ATUs will be discussed in section 14.10 Antenna Tuning Units.

The earlier mentioned circuit in section 8.3.1 was not resonant but capacitive, with 66 Ω capacitive reactance, on 2 MHz. To bring it into resonance on 2 MHz we could add 66 Ω of inductive reactance to it. To achieve a result that is close enough, one could connect an inductor that has inductance of 5 μH, in series, with that circuit.[135]

8.3.3 Impedance

Reactance and resistance are the fundamental properties of any circuit used in radio. They both present an opposition to the changes of current. Resistance and reactance impede the flow of alternating current. The combination of reactance and resistance is called IMPEDANCE. Its unit is ohm (Ω) and its dimension symbol is letter Z.

For example, the characteristic impedance[136] of coaxial cables commonly used to connect radio equipment to antennas is 50 Ω.

The impedance is known to be PURELY RESISTIVE if a circuit has no reactance. For example, coaxial transmission lines have no reactance at amateur radio frequencies. Circuits that are resonant on a given frequency also have no reactance. In both of those cases the impedance is purely resistive, it is not REACTIVE.

Impedance of circuits that have some reactance changes with the frequency because their reactance depends on the frequency. On the other hand, since coaxial cables do not have reactance, their impedance is purely resistive, regardless of the frequency.[137]

134 Instead of using variable components, ATUs can also have a set of fixed inductors and capacitors of different values, which can be included or excluded from the circuit as needed, by using relays. That is why many ATUs click when they are searching for a combination of capacitors and inductors needed to eliminate reactance. Additionally, the desired impedance match may require more than cancelling the reactance. ATUs also need to match the resistive component of impedance.

135 While this approach works for all circuits, including antennas, there are better ways to make an antenna resonant than by adding inductors or capacitors to it. Adjusting the length or geometry of an antenna and its components can make it resonant without causing additional losses. See 15.9 Non-resonant Wire Antennas and Multiband Antennas.

136 Characteristic impedance, Z_0, will be discussed in section 14.1. It is defined as the input impedance of an unconnected, infinitely long transmission line. Even though practical cables are always finite in their length, this number is useful. Connecting equipment matching it ensures the best conditions for the operation of your station.

137 Coaxial cables have no reactance at the frequencies at which we use them for radio. At much lower, audio frequencies, they do have some reactance. For example, the popular RG-58 coaxial cable has some non-negligible reactance at frequencies below 10 kHz. As a result, its characteristic impedance increases below those frequencies, and it is no longer 50 Ω. It can become as high as 240 Ω at 1 kHz.

In theory, it could be possible to have a circuit that is only reactive, with no resistance, however, such circuits do not exist in practice. All circuits have some resistive component in their impedance.

Impedance that is not purely resistive is either an INDUCTIVE IMPEDANCE or a CAPACITIVE IMPEDANCE, depending on its reactance.

8.3.4 Impedance as a Number

The exam syllabus does not require you to know how to calculate the magnitude of impedance, nor how to express it as a complex number. You can skip subsections 8.3.4.1 and 8.3.4.2 while revising for the exam. However, you will find this material useful in practice, when working with non-resonant antennas and ATUs, and it should help you understand their principles, discussed later in the guide.

There are two ways to express impedance: as its two components, resistance, and reactance, or as a single, complex number.

8.3.4.1 *Complex Impedance*

This subsection is not part of the exam syllabus.

Let's consider a circuit, such as an antenna that has a resistance R of 50 Ω, and a reactance X of 100 Ω. This antenna is inductive because the reactance is a positive number. It has inductive impedance. As explained in 8.3.1, if the reactance were a negative number, such as −100 Ω, that antenna would be capacitive rather than inductive.

The first way to express the impedance of this antenna is to write both the resistance and the reactance in the following way:

$$Z = 50\,\Omega + j\ 100\,\Omega$$

This is known as COMPLEX IMPEDANCE. In this approach, the reactance is always preceded by the lowercase letter j.

This way of expressing a quantity, that consists of two closely related, but different numbers, is known as a COMPLEX NUMBER in physics and mathematics. It is popular because it allows both components of a quantity to be easily seen. In the case of impedance, the first part, the resistance, is known as the REAL PART of the complex impedance. The second part, the reactance, which is always preceded by the letter j, is known as the IMAGINARY PART of the complex impedance. Letter j is known as the IMAGINARY UNIT, a mathematical quantity that has the unusual property that if it were multiplied by itself, that is raised to the power of two, it would yield a negative number, *minus one* $j^2 = -1$. Letter i is used instead of letter j in sciences other than electromagnetism. Letter j was chosen in electrical theory not to confuse it with the dimension symbol of current, the capital letter I.

This is a useful notation because it allows us to know both the resistive and the reactive aspect of a radio component. For example, if you needed to make this antenna resonant, you would know that by adding 100 Ω of capacitive reactance

($-100\,\Omega$) you could cancel the inductive reactance, and the impedance would become purely resistive.

8.3.4.2 *Magnitude of Impedance*

This subsection is not part of the exam syllabus.

Alternatively, it is possible to express the impedance of such a circuit by calculating a single number, known as the MAGNITUDE OF IMPEDANCE, and denoted $|Z|$ using this formula:

$$|Z| = \sqrt{R^2 + X^2}$$

In the case of the above antenna, the magnitude of its impedance would be:

$$|Z| = \sqrt{50^2 + 100^2} = \sqrt{2500 + 10000} = 111.8\,\Omega$$

This value is useful for calculations using Ohm's law, which require a single number, to find out voltage rms or current rms.

For circuits that are purely resistive, i.e., which have no reactance, the magnitude of impedance is equal to its resistance. That is the reason why characteristic impedance of a transmission line, such as a coaxial cable, is written as a single number, rather than as a complex impedance.

Unfortunately, it is easy to confuse magnitude of impedance, calculated for a reactive circuit, such as a non-resonant antenna, with the characteristic impedance of a purely resistive transmission line. As a result, a mistake can be made in assuming that a perfect match would exist between a non-resonant antenna whose magnitude of impedance equals the characteristic impedance of the transmission line. It is safer to rely on the complex impedance of any reactive circuits than try and simplify matters to a single number which may hide the reactive aspects of that circuit.

8.4 Tuned Circuits, Filters, and Q Factor

By far the most important resonant circuits in radio design are tuned circuits. This section discusses the two of the simplest and most important ones: series tuned circuits and parallel tuned circuits. You will also learn about their most important application: to make filters. Finally, the subsection will introduce digital filters and the Q factor: a way of comparing the bandwidth and the performance of resonant circuits.

8.4.1 Series and Parallel LC Circuits

TUNED CIRCUITS, also known as RESONANT CIRCUITS, are circuit comprised of an inductor and a capacitor. They are also known as LC CIRCUITS, because letters L and C represent inductance and capacitance, respectively.

Circuits with inductance and capacitance connected in series were already introduced in the previous three sections. Those circuits are known as SERIES TUNED CIRCUITS, or SERIES LC CIRCUITS. An example is shown in Figure 8-xiii.

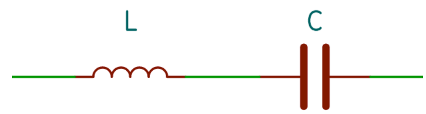


Figure 8-xiii: Series LC circuit. [EI9ILB]

It is also possible to connect the inductor and the capacitor in parallel, into a PARALLEL TUNED CIRCUIT, also known as a PARALLEL LC CIRCUIT, shown in Figure 8-xiv.

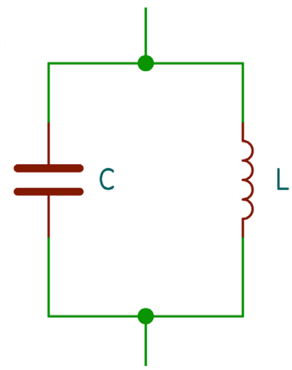
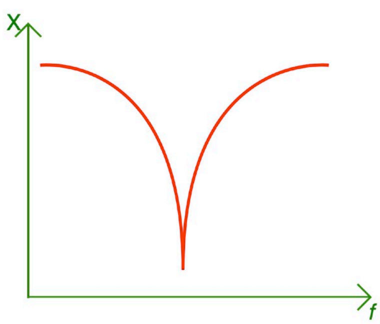


Figure 8-xiv: Parallel LC Circuit. [EI9ILB]

All tuned circuits have a resonant frequency. It is interesting to note what happens with their reactance, and therefore their impedance, outside of their resonant frequency.

Series LC circuit has a *low* impedance at resonance. It is known as an ACCEPTOR circuit, and it will pass signals through at its resonant frequency, if connected in *series* with a load. Figure 8-xv shows the impedance of such a circuit at and outside of its resonant frequency.



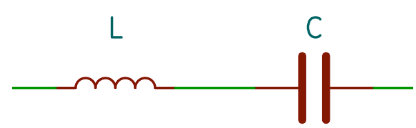


Figure 8-xv: Impedance of series LC circuits, when connected in series with a load. Impedance on the vertical axis, frequency on the horizontal. Resonant frequency is in the centre, where the impedance is lowest. [EI9ILB]

On the other hand, parallel LC circuit has a *high* impedance at resonance. It is known as a REJECTOR circuit and it will block signals at its resonant frequency, if connected in series with a load, see Figure 8-xvi on the next page.

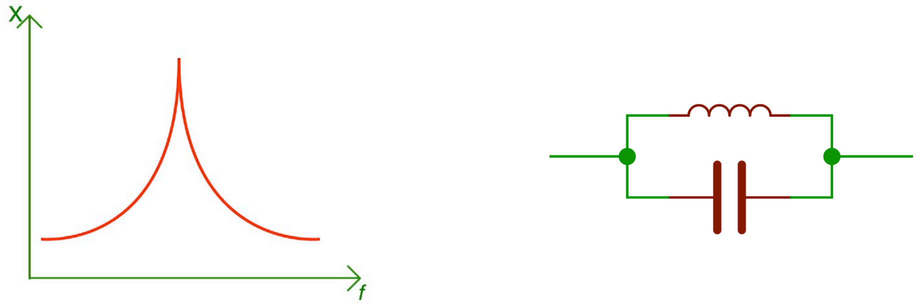


Figure 8-xvi: Impedance of parallel LC circuits, when connected in series with a load. Impedance on the vertical axis, frequency on the horizontal. Resonant frequency in the centre, where the impedance is the highest. [EI9ILB]

Try to understand why a series LC passes and a parallel LC blocks their resonant frequencies, when connected in series with a load. Look at their circuit diagrams and trace which way the signal could go. Remember that inductors pass low frequencies and block high ones, while capacitors do the opposite, they block low frequencies but pass the high ones.

In the series LC circuit, the signal has to go through both components, the capacitor, and the inductor. Both the low and the high frequencies will be opposed by either of the two components. Only the resonant frequency, in the middle, will be opposed the least by each component, and will pass through a series LC. This is a BAND-PASS FILTER.

In the parallel LC circuit, the signal has two pathways that it can travel, because there are two branches in that circuit, see Figure 8-xiv. One branch has the capacitor, and the other branch has the inductor. Low frequency signals will pass through the branch containing the inductor, even if it is impeded by the other branch. High frequency signal will pass through the capacitor branch, even if it is impeded by the other branch. As a result, both low and high frequencies pass through a parallel LC. However, the resonant frequency, which is somewhere in the middle, is now too high to pass unimpeded through the inductor branch and too low to make it through the capacitor branch. As a result, resonant frequency is blocked by a parallel LC. This is a BAND-STOP FILTER.

The two circuits, LC series and LC parallel, were discussed and shown as being connected IN SERIES WITH A LOAD. It is also possible to connect those circuits IN PARALLEL WITH A LOAD. Circuit diagrams sometimes show the return path drawn as a line, which may represent a second wire of an antenna cable, the interior of the shield of a coaxial cable, or a ground trace on a printed circuit board. Sometimes it is possible to utilise the shared, common path to the earth or a ground, or a metal chassis of a device. For those reasons, circuit diagrams showing filters sometimes show a dedicated signal return path, usually as a line at the bottom of the diagram, and sometimes as a symbol representing the chassis or the earth. Figure 8-xvii shows both examples, however, later diagrams will show a line representing the signal return path.

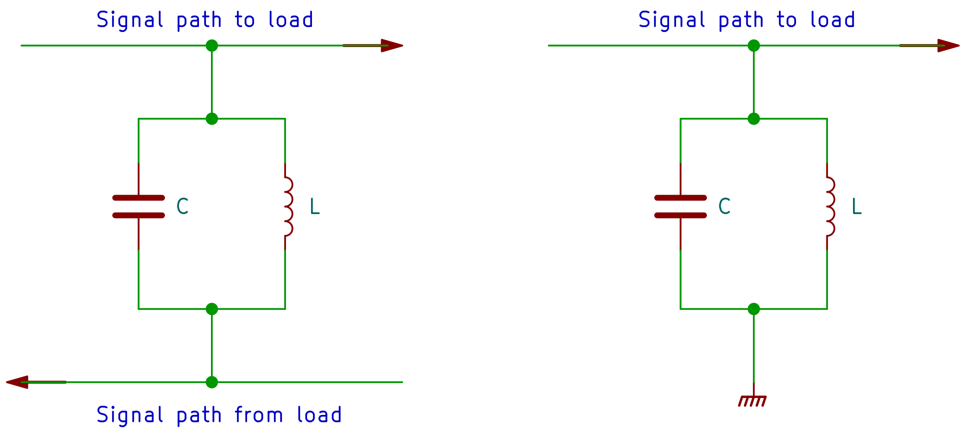


Figure 8-xvii: LC parallel circuit connected in parallel with a load. The line on top represents signal going from a source to the load. Signal returning from the load to the source can be shown using a line (left) or a common chassis ground (right). [EI9ILB]

The behaviour of LC circuits can be reversed by connecting them in parallel, rather than in series, with a load. Figure 8-xvii shows a parallel LC circuit connected in parallel with a load. Table 8-A summarises the behaviour of LC circuits when connected in series, and the reversed behaviour, when connected in parallel with a load.

Table 8-A: LC circuits in series and in parallel with a load

LC circuit type	Load connected in series	Load connected in parallel
Series LC	Band-pass	Band-stop
Parallel LC	Band-stop	Band-pass

Both types of LC circuits can be used for the same purpose. For example, a series LC circuit connected in parallel with a load can be used as a band-stop filter to stop a narrow range of unwanted frequencies, fulfilling the function of a NOTCH FILTER.

If you are wondering why connecting those LC circuits in parallel with the load has the effect of reversing their series-connected behaviour, let's consider a series LC first. Figure 8-xviii shows the two ways how it can be connected with a load: either in series, or in parallel with the load. The line on top represents the path of the signal from a source to the load, and the bottom line represents the return path of the signal from the load back to the source.

Let's look at the different routes a signal can take to pass through those two circuits.

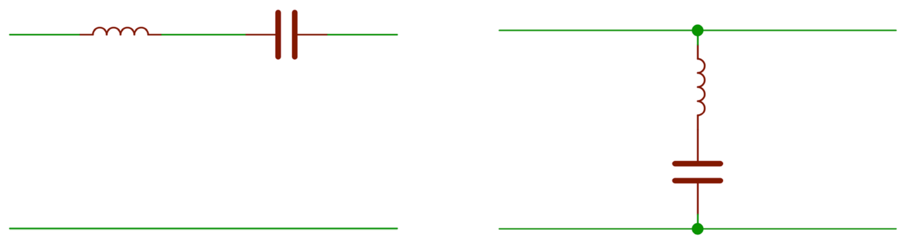


Figure 8-xviii: LC series connected in series (left) and in parallel (right) with a load. Line on top represents the signal path to the load. The bottom line is the return from load to source. [EI9ILB]

When series LC is connected in series with the load, as shown on the left in Figure 8-xviii, signal passes through it on its way to the load. Series LC passes frequencies at resonance and stops those below and above it, behaving as a band-pass filter. However, when you connect series LC in parallel with the load, as shown on the right, signals at the resonant frequencies are now being connected to the signal's return path to source, instead of the load. You can think of those signals, at resonant frequencies, as being shorted, or grounded. Instead of reaching the load, the resonant frequencies of a series LC connected in parallel with a load come back to the source. On the other hand, signals at frequencies below and above the resonant ones, which cannot pass through the series LC, are not being sent back to the source by it. Instead, they just continue to the load. The result is a band-stop filter, the opposite of a band-pass filter.

LC circuits connected in parallel with a load essentially connect signals back to the source, via the chassis, a common ground, or the earth, instead of connecting them to the load. As a result, their function is the opposite of what they do in their more natural way of being connected in series with the load.

Section 8.4.2.2 will discuss the different filter types. You will also see diagrams showing how the two LC circuits can be connected in series and in parallel with a load, in particular in Figure 8-xxii and Figure 8-xxiii.

8.4.2 Filters

A FILTER is an electronic or a digital component that either removes or ATTENUATES (reduces) unwanted frequencies of a signal. As a result of reducing or removing what is unwanted, the remaining frequencies are enhanced. All receivers and transmitters, and much of other radio equipment contains many filters.

Filters have a great number of uses in radio. They are necessary to ensure that you only hear the transmission you are interested in on a given frequency, rather than all the transmissions jumbled together. They remove noise. They enhance weak signals and make them more pleasant to hear. They allow an antenna to be used simultaneously by multiple receivers and transmitters on different frequencies. They prevent distortion and even protect equipment from damage caused by excessive signals on frequencies that you are not interested in. They remove unwanted harmonic emissions letting your transmitter meet regulatory requirements. They prevent nuisance

such as key clicks. They are a necessary component to modulate and to demodulate signals impressed on carrier waves. There are many other uses of filters, but it can be safely said that they are the most important resonant circuit in radio design. This section will introduce the key aspects of filter design that are required by the exam syllabus. If you are interested in building your own equipment, you should seek further knowledge in this interesting area.

8.4.2.1 *Filter and Tuned Circuit Bandwidth*

A bandwidth is the difference between the lowest and the highest frequency of a range of frequencies.

The HALF-POWER BANDWIDTH of a circuit is the bandwidth at which the circuit resonates (vibrates) with at least half of the power, in watts, that it has at its resonant frequency. It is also known as the −3 dB BANDWIDTH because a reduction by 3 dB represents the halving of the power. It is usually denoted with the letter B.

Recall from section 3.10.2 Power and Ohm's Law that power is a determined from the voltage and resistance (or current and resistance):

$$P = \frac{V^2}{R}$$

The half-power point occurs when the amplitude of a signal, that is, its voltage, is about 70%, or 0.7071 of its peak value, at the resonant frequency.[138] This is illustrated in Figure 8-xix.

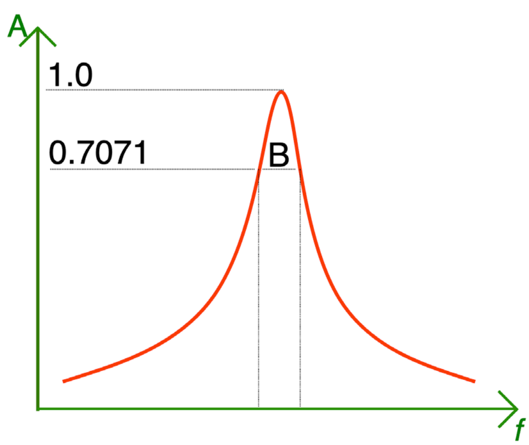


Figure 8-xix: Half-power bandwidth, B. Frequency on the horizontal axis, amplitude on the vertical axis. 0.7071 indicates the point at which the circuit power is half of what it is when the amplitude is at its maximum of 1. [EI9ILB]

138 0.7071 is approximately equal to $\sqrt{(1/2)}$. This represents the amplitude as voltage V when halving the power P. The square root arises because of the square of the voltage, V^2, in the formula for power. As the resistance of this circuit does not change when the voltage is reduced, the current must reduce in tandem.

8.4.2.2 *Frequency Response of Different Filter Types*

The diagram in Figure 8-xix can be also interpreted as a FREQUENCY RESPONSE DIAGRAM of a filter. Reading it in the most direct way, that filter could be used to pass frequencies centred around its resonant frequency, and to reduce those below and above it, almost entirely removing much lower and the much higher frequencies. This would be an example of a band-pass filter, one of the four of the most important filters in radio.

The four diagrams on the right-hand side in Figure 8-xx show idealised frequency responses of the four basic filters.

a LOW-PASS — passes low frequencies, stops high
b HIGH-PASS — passes high frequencies, stops low
c BAND-PASS — passes a range of frequencies and stops (rejects) frequencies outside the passband
d BAND-STOP — rejects a range of frequencies and passes all others. If the transition is sharp enough it is also called a NOTCH FILTER

No practical filter can cut off frequencies with such a steeply sharp response as the almost straight lines suggest in these diagrams. The typical response is smoother and depends on the design of the filter. It can be described by the filter's SHAPE FACTOR which is the ratio between the two bandwidths: where the filter is able to reduce the power of the signal by −6 dB, and the bandwidth of its −60 dB reduction of power. This is illustrated in Figure 8-xxi, which also shows other common terms used to describe filter responses, such as STOPBAND and the TRANSITION BAND.[139]

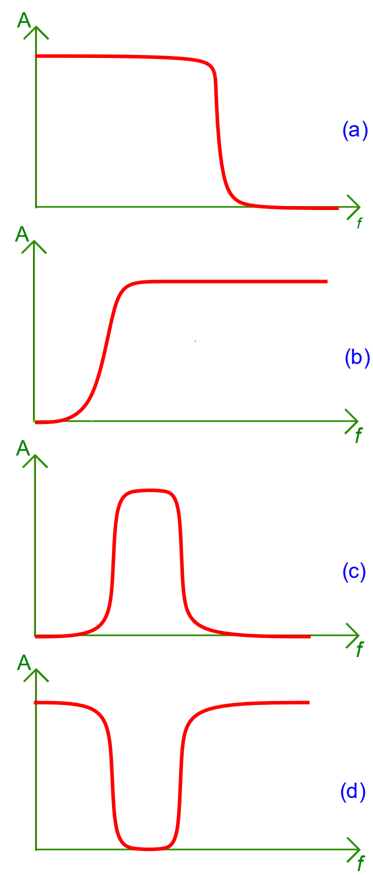


Figure 8-xx: Types of filters. Amplitude on the vertical axis, frequency on horizontal. [EI9ILB]

139 Stopband of a filter is the range of frequencies that the filter will attenuate so much that they can be considered to have been removed. In the drawing there are two stopbands, one below and one above the passband. Transition band represents a narrow range of frequencies that are somewhat, but not yet fully attenuated by the filter. The shape factor, and the Q factor, determine how steep the transition bands are. A shape factor ratio of 2:1 is generally considered acceptable.

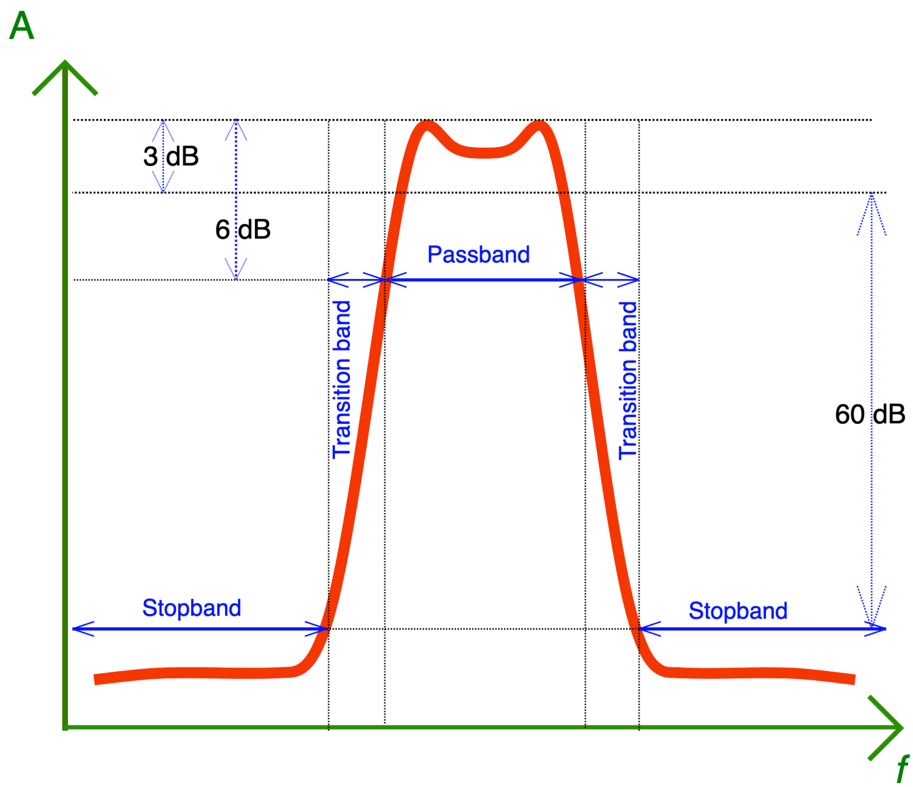


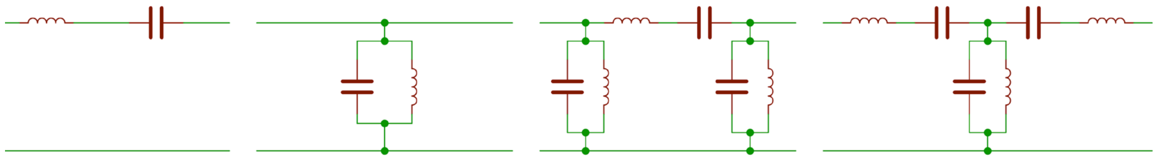
Figure 8-xxi: Filter response shape for a band-pass filter. Response, on the vertical axis, is the signal's amplitude, usually, voltage. This is a simplified diagram that ignores filter losses. In a realistic filter even the amplitude at the maximum response of a filter, represented by the topmost horizontal line, would be less than that of the signal. [EI9ILB]

There are many ways to build filters using resonant circuits. Below you will find a few common designs, which you need to be able to recognise.

Please refer to Table 8-A: LC circuits in series and in parallel with a load while studying the band-pass and band-stop circuit diagrams below as that will clarify why they function that way.

Note that some of the filter designs have friendly names, such as T or Pi filters. This is due to the similarity of their circuit layout to letters T and Π (Greek capital letter pi or π).

While you are studying the filter circuits shown on the next page it may be helpful to notice that they all have *two* signal paths: one is on the top of each circuit, and one on the bottom. Each path also has two terminals: on the left and on the right of each circuit. The path on top is the path of the signal going from the source, which may be on the left, to the load, which may be on the right. The path on the bottom represents the return of the signal from the load back to the source. This return can use a dedicated wire, or a connection to a chassis common conductor, a ground, or an earth. Notice how connecting series and parallel LC circuits in series with the load leaves the return path intact: see the bottom path on the very left in Figure 8-xxii and on the right in Figure 8-xxiii.



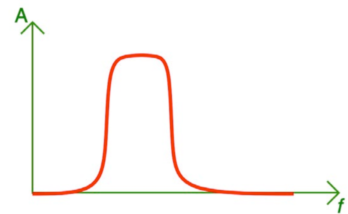


Figure 8-xxii: Band-pass filters, from left. 1. Series LC connected in series. 2. Parallel LC connected in parallel. 3–4. Cascaded filters: instead of using a plain inductor or a capacitor, a simple filter is used as a building block of a more complex one, giving a better filter response shape. Design 4 is also known as a T filter because it resembles letter T. [EI9ILB]

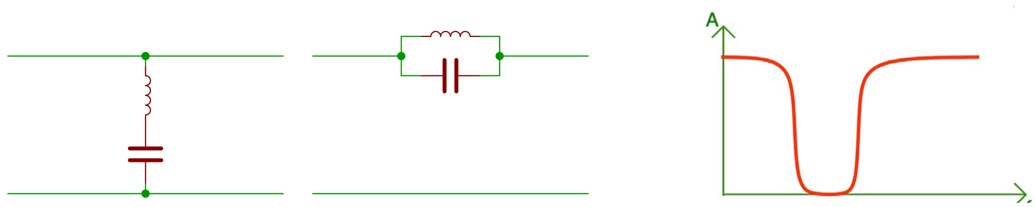


Figure 8-xxiii: Band-stop filters. Left: series LC connected in parallel. Right: parallel LC connected in series. [EI9ILB]

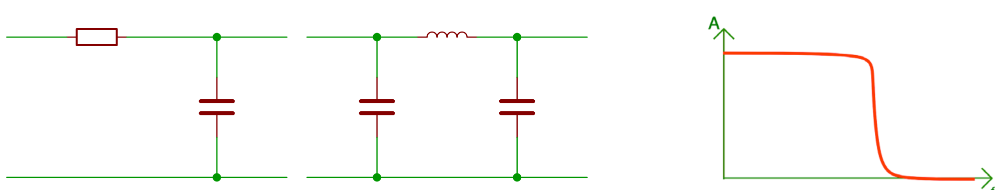


Figure 8-xxiv: Low-pass filters. Left: notice the resistor. Right: Pi filter because it looks like Greek letter Π (pi). Observe that in these examples of *low-pass* filters the capacitors appear *below* the signal path (the upper line). [EI9ILB]

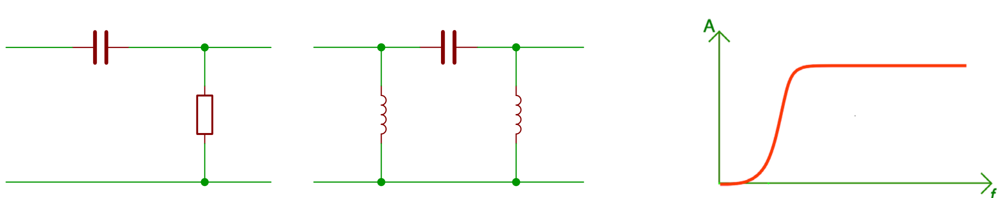


Figure 8-xxv: High-pass filters. Left: notice the resistor. Right: Pi filter. Observe that in these examples of *high-pass* filters the capacitors appear on the signal path (the *high,* upper line). [EI9ILB]

8.4.3 Digital Filters

The digital terminology used in this section has been introduced in Chapter 6.

DSP, and by extension SDR, provide a different way of implementing filters. Instead of using tuned circuits, software can be written to perform filter functions on the digitised, sampled signal. The two DIGITAL FILTER designs, discussed below, which have been fundamental to DSP work in the time domain of the signal, not requiring a conversion using an FFT. More recent, complex digital filters operate on signals converted into their frequency domain, necessitating the use of FFT. Modern digital radios use all of those techniques.

INFINITE IMPULSE RESPONSE, IIR, filters can represent all traditional electronic designs, including the four mentioned in the previous subsection. Any combination of resistors, capacitors, and inductors can be represented as an IIR filter. A unique advantage of IIR filters is that they can produce a very sharp transition region that would be difficult or expensive to build using electronic components.

FINITE IMPULSE RESPONSE, FIR, filter design is more unique to digital filters.[140] This design can be more complex. It can require more computing power than an equivalent IIR filter, and tends to be used for specialised purposes, such as phase filtration. It allows more freedom in filter design than IIR, which tends to resemble traditional electronic filter designs.

Digital filters are only limited by the quality of the sampling and digital synthesis processes, which, in turn, are limited by the computational abilities of the hardware integrated circuit computer chips, on which the software runs. With suitable hardware, advanced designs can be built using digital filters that would not be economical using tuned circuits.

However, traditional electronic, analogue, i.e., not digital filters have significant advantages, notably with regards to power handling and their immunity from excessively strong nearby signals. Digital filters do *not* handle high-power applications yet. The reason for that limitation is the limitation of DACs. First, AC signal needs to be digitised before it can be digitally filtered, which is not difficult. However, after any digital filtering, it would have to be converted back to a high-power AC. DACs can only generate relatively low-power signals. To use a digital filter in a high-power circuit would require the use of a high-power amplifier after the DAC. Because, at present, it is not possible to build high power amplifiers using software alone, the need for such additional analogue circuitry means it is still simpler and more economical to use traditional electronic circuits to build filters that work with high-power signals.

Similarly, digital filters used for receiving purposes are not able to handle any nearby, i.e., slightly out of band, strong, high-power signals. Analogue band-pass

140 The name of IIR filters is related to the theory of their operation. They are capable of producing an impulse response of an infinite duration. FIR filter response has a finite duration, meaning that their impulse response becomes zero after a number of cycles. In terms of the software design, IIR filters have loops, or more precisely, have a recursive design, which functions like a feedback loop. They use an output of a previous calculation as an input for a subsequent one. FIR filters do not rely on feedback. They are designed without such loops and resemble more traditional software.

filters are necessary to filter such out-of-band strong signals, before they could be processed using an ADC.

Those are some of the reasons why SDR transceivers combine the use of digital filters for the purposes at which they excel, such as sharp notch or phase noise filtering, with traditional designs, such as band-pass filters.

8.4.4 Q factor

The Q FACTOR (QUALITY FACTOR) determines the bandwidth of resonant circuits, including antennas. A circuit with a high Q has a narrow bandwidth, while low Q represents a wide bandwidth, see Figure 8-xxvi.

There are no ideal inductors and capacitors, therefore, there are no ideal, lossless tuned circuits. All tuned circuits have some loss resistance and lose some power to heat. Similarly, there are no ideal crystals, and they also lose some power to mechanical friction.

Q factor of an inductor and a capacitor can be calculated from its reactance and resistance:

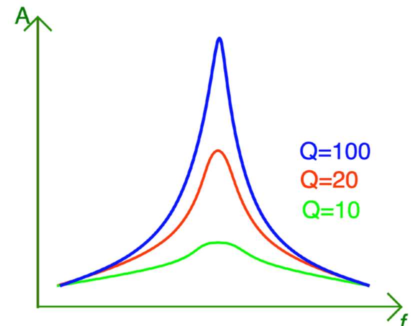


Figure 8-xxvi: Bandwidth of different Q factors, frequency on horizontal axis, amplitude on the vertical axis. [EI9ILB]

$$\mathrm{Q} = \frac{X_\mathrm{L}}{R_\mathrm{L}} \qquad \mathrm{Q} = \frac{-X_\mathrm{C}}{R_\mathrm{C}}$$

High Q of a component is obtained by having a much higher reactance than resistance.[141] When reactance becomes close to resistance, the Q becomes lower, and the bandwidth grows, which means that the component is no longer resonant on a very specific frequency, but it resonates, albeit to a lesser extent, on a wider range of frequencies. Q factor does not have a unit, it is just a number on its own, as it expresses a ratio.

The Q factor also determines the losses in a resonant circuit. This is directly related to how long the circuit could sustain its oscillations if it were not losing power. A high Q circuit is more efficient at storing and transferring energy at its resonant frequency.

Another way to find the Q factor of a component, or of an entire resonant circuit, is to use its resonant frequency f_{res} and the half-power bandwidth B. This calculation of the Q factor is particularly useful for filters. See also 8.4.2.1 Filter and Tuned Circuit Bandwidth.

$$\mathrm{Q} = \frac{f_{res}}{B}$$

141 Q factor of a series LC circuit can be also calculated from its components $Q = {}^{1}\!\Big/\frac{1}{Q_L} + \frac{1}{Q_C}$

8.5 Quartz Crystals

A QUARTZ CRYSTAL is a naturally occurring mineral that can be mined. It has an interesting property. If it is mounted between two electrodes it will generate a voltage when it is mechanically squeezed or deformed. It also works in the opposite direction. When voltage is applied to the crystal, it will deform itself. This behaviour is known as the PIEZO-ELECTRIC EFFECT.[142]

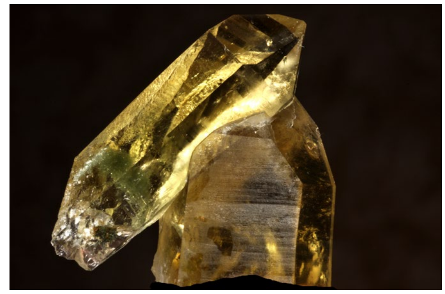


Figure 8-xxvii: Naturally occurring quartz crystal. [Image by Parent Géry, see page 375]

Most usefully, each crystal has its own resonant frequency. If an alternating current at that exact frequency is applied to it, the crystal will vibrate, and while vibrating, it will allow that frequency of AC to pass through it. The resonant frequency vibrations of a crystal will self-sustain with only very small amounts of current needed.

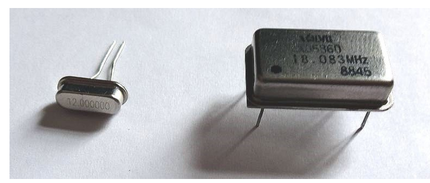


Figure 8-xxviii: Crystal oscillators: 12 MHz (left) and 18.083 MHz (right). [Image by Vahid alpha, see page 375]

In addition to resonance at its fundamental frequency the crystal can vibrate and exhibit resonance on OVERTONES, which are the odd harmonics (3rd, 5th, ...) of its fundamental resonant frequency.

Because the resonance of the crystal happens only when the frequency is very exact, it makes for a high-quality device. It can be used to make very accurate filters.

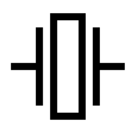


Figure 8-xxix: Schematic symbol of a quartz crystal component. [EI9ILB]

Quartz crystals are also often used to make accurate and stable oscillators.

8.6 Oscillators

Radio technology extensively uses sinusoidal signals at desired frequencies. There are different methods to generate them, some of which are discussed in this subsection.

As explained in Chapter 5, AC is a sinusoidal signal. The purpose of an electronic OSCILLATOR is to generate AC at the desired frequency from a DC supply. The

142 If you have used a lighter that produces a spark when you press a button, you have seen the piezo-electric effect. A hard push on the button squeezes a quartz crystal and it generates a high enough voltage to send a spark between two electrodes. Not all lighters are piezo-electric. Some have batteries, yet others produce sparks when you rotate an abrasive knob against a piece of flint.

generated currents are often in the form of a sine wave, but other periodic non-sinusoidal forms can be also generated, such as a square wave.[143]

Oscillators are a fundamental building block in most electronic devices. They can generate AC at many frequencies, including AF of 0–20 kHz, and all RF, from a few kHz to GHz and more.

Discreet components, such as capacitors and inductors, can be used in oscillator design. However, for radio frequency design, oscillators are more likely to be implemented using crystals. They use the mechanical resonance of a vibrating crystal to generate a sinusoidal electronic signal at a very precise frequency. Even digital technologies, including computers and SDR, rely on crystal oscillators to generate highly precise sinusoidal signals, used for the timing and synchronisations of other processes.

In amateur radio, oscillators are used to perform many functions. You will see all of the following types of oscillators in the block diagrams discussed in Chapters 12 Transmitters and 13 Receivers.

- CARRIER WAVE OSCILLATOR, also known as a MASTER OSCILLATOR, , is used to generate RF carrier waves. In the simplest of all transmitters, the carrier wave generated by a master oscillator may be interrupted, i.e., turned either on or off, using a key, at any point on its way to the antenna. This is how a Continuous Wave (CW) transmitter sends Morse Code, consisting of short (dit, dot) and long (dah, dash) transmissions of the carrier wave.[144] Master oscillator is also used for transmitting more complex information, such as voice, video, or data. In those cases, the carrier wave is modulated to carry that information. See Chapters 11 Modulation and Modes and 12 Transmitters.
- LOCAL OSCILLATOR (LO) is used to mix a pure sine wave with an incoming radio signal in a receiver to change the incoming frequency to higher and lower frequencies than that of the incoming frequency. You will learn more about this important principle in Chapter 13 Receivers.

143 Recall that a periodic wave is one that has the same shape (form) repeating itself over and over. Sine wave is a periodic wave: it has a period, wavelength and a frequency – see section 5.1 Sinusoidal Signals. Non-sinusoidal signals that have been discussed in section 6.1 Non-Sinusoidal Signals were generally non-periodic in nature, that is, their shape was varied rather than repeating. However, it is possible to have non-sinusoidal waveforms that are periodic, repeating the same form, and therefore having a period, wavelength, and a frequency. An example of that is a square wave, triangular wave, or a sawtooth wave. They have some uses in radio and audio. See en.wikipedia.org/wiki/Square_wave.

144 It may sound like a contradiction that an *interrupted* carrier wave is named *continuous*. The name of CW is historical. Spark gap transmitters were invented by Heinrich Hertz in 1887 heralding the era of wireless telegraphy. A spark gap generated a series of very brief pulses of many different frequencies. Those were known as *damped waves* because the pulsed waves decayed quickly. Damped waves of the spark gap technology were inefficient because they spread the signal over an unnecessarily wide bandwidth, causing significant radio frequency interference, and requiring much power. It was soon discovered that by making the waves last longer the bandwidth and efficiency could be improved, leading to the idea of making the wave continuous. Initially, it was called an *undamped wave*. It replaced the pulsed, spark gap damped waves around 1920 thanks to the discovery of vacuum tubes. Spark gap transmitters and damped waves were discontinued and made illegal in 1934. See en.wikipedia.org/wiki/Continuous_wave and en.wikipedia.org/wiki/Spark-gap_transmitter

- BEAT FREQUENCY OSCILLATOR (BFO) is used to make received CW transmissions audible. The BFO generates a signal which is mixed with the output of the IFfrequency) to produce an audio signal that can be then amplified by an AF amplifier and passed to a speaker.[145]
- CARRIER INSERTION OSCILLATOR (CIO) performs a similar task to a BFO. It is used to restore the carrier wave in a receiver that has been suppressed by a single sideband (SSB) transmitter. This is part of the process of demodulating SSB signals to make them audible.
- VARIABLE FREQUENCY OSCILLATOR (VFO) is used in transmitters and receivers to precisely vary the frequency over a range. This is necessary when tuning a transceiver to a desired frequency within a chosen band. VFO is also a common way to refer to the tuning knob on a transceiver.

8.6.1 Resonant Circuit Oscillator

An oscillator can be constructed from a resonant circuit acting as a filter, such as a tuned (LC) circuit, or a quartz crystal, and an amplifier.

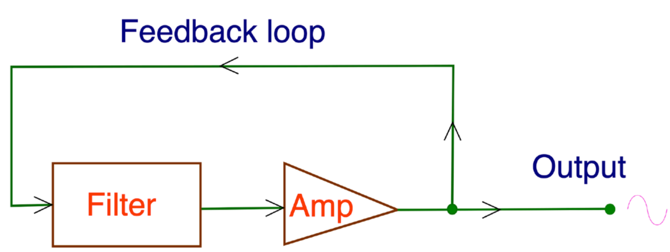


Figure 8-xxx: Oscillator design using an amplifier and a resonant circuit as a filter that determines the generated signal frequency. [EI9ILB]

An example of a practical oscillator design is an amplifier with a positive feedback loop provided by a resonant circuit that is acting as a frequency filter. As a result, the resonant circuit determines the desired frequency. The filter also makes it possible to extract harmonic frequencies (overtones) if desired. More accurate oscillators are built using crystals instead of LC circuits, especially for generating radio frequencies.

145 IF is used in several aspects of radio design. It is a key concept of a superheterodyne receiver, which will be discussed in section 13.1.

9 Power Ratios and Decibels

RELATED EXAM SECTIONS · A1 A3 A4 A6

You need to understand how decibels are used to express power and power ratios in many aspects of radio theory and practical use. They are particularly important when considering amplifiers, transmission line losses, antenna gain, and safety. However, you will hear people use decibels even during casual on-air contacts, when reporting their signal strengths using the RST code, see section 29.5.

9.1 Decibel

DECIBEL is a handy way of expressing ratios. A RATIO tells us how much bigger, smaller, stronger, or weaker something is than something else. It is a relative, rather than an absolute, unit of measurement. The symbol of a decibel is **dB**.

For example, you may want to say that the power of the signal you output from an amplifier is ten times as strong as the signal that goes into it. This is very easy with decibels: you just say your amplifier adds 10 dB of power.[146] If your amplifier was switched off and the output power was the same as the input, it would not have added any additional power to the signal, zero dB.

There are many uses of decibels. You have already seen them used to express signal-to-noise ratios, SNR, and dynamic ranges of SDR receivers and transmitters in section 6.3.3 Sampling Rate and Resolution, and to express half-power bandwidth of filters in section 8.4.2. You will see them used again many more times in this guide, when discussing receiver characteristics, in section 13.7.1 Sensitivity and Signal-to-Noise Ratio (SNR), when discussing antennas in section 15.15 Directivity, Efficiency, and Gain, and to express power in 15.20 Effective Power: EIRP and ERP.

It is easy to remember that a ratio of 10 is 10 dB. Other ratios are a little more complex because the decibel follows a logarithmic (base 10) rather than a linear scale. This extra complexity is very valuable and worth the effort to understand it. It allows us to simply add the decibels together, instead of having to multiply the ratios, for example when calculating the overall signal power as it goes from your transmitter, through the coax cable, and out of the antenna.

For the the exam, you need to know only the approximate ratios of the decibel values shown in Table 9-A, and not the true power ratios. It is particularly helpful to memorise the meaning of 10, 3, and −3 dB, as the remaining ratios can be readily calculated from those three.

146 You may recall that letter d is a metric prefix for *deci,* meaning a *tenth* of something, see Table 3-B: Selected SI metric prefixes. This means 1 dB = 0.1 B and 10 dB = 1 B. The actual unit of measurement is called a *bel* and its symbol is B. The smaller deci·bel is much more common than its bigger parent, the bel. However, it would be absolutely correct to state power ratios in bels. In the case of our amplifier which adds 10 dB of power, making the signal ten times stronger, you could write that it adds 1 bel, or 1 B of power.

Table 9-A: Decibels as ratios

dB	Approximate power ratio	True power ratio
30 dB	1 000 times	1 000
20 dB	100 times	100
10 dB	**10 times**	10
9 dB	8 times	7.943
6 dB	4 times	3.981
3 dB	**2 times**	1.995
0 dB	one	1
-3 dB	**half (1/2)**	0.501
-6 dB	quarter (1/4)	0.251
-10 dB	one tenth (1/10)	0.1
-20 dB	one hundredth (1/100)	0.01

9.2 Power Ratios

The most common use of a decibel is to express POWER RATIOS, for example, the ratio of input to output power of an amplifier or a transmission line, or to compare the power radiated by an antenna in a particular direction to another reference antenna.

9.2.1 Power Ratios in Watts as Decibels

To calculate the ratio, simply divide the output by the input power in watts, then use the table above to find the decibel value.[147]

For example, if output of an amplifier is 1 000 W when it is supplied with 10 W input power, then:

$$\frac{1\,000\text{ W}}{10\text{ W}} = 100 = 20\text{ dB}$$

9.2.2 Power Ratios using Voltage or Current as Decibels

Power ratios can be also calculated using voltage or current, however, the decibel formula is slightly different. First, you follow the steps above, that is, divide output voltage (or current) by the input voltage (or current). Look up the nearest value in the table, then multiply the found dB value by two.[148]

147 The precise formula of calculating that ratio is $\text{dB} = 10\log_{10} ratio$. In our example that would mean $10 \times \log_{10}(100) = 10 \times 2 = 20$ dB. If you are wondering why there is number 10 at the front of that formula, that is because without it you would calculate the ratio in *bels* and not decibels.

148 The formula for *voltage* or *current* power ratio is $\text{dB} = 20\log_{10} ratio$. In this case: $20\log_{10}(100) = 20 \times 2 = 40$ dB. The reason for 20 instead of 10 is because power expressed as voltage or current using Ohm's Law requires voltage (or current) to be *squared,* i.e., multiplied by itself. Because decibels are logarithmic, squaring a number is equivalent to multiplying it by 2.

For example, if the output of an amplifier is 1 000 V when fed with 10 V input, the power ratio in dB is:

$$\frac{1000\ \text{V}}{10\ \text{V}} = 100 = 20\ \text{dB} \times 2 = 40\ \text{dB}$$

9.3 Absolute Power in Decibel-Watts

Another common use of decibels is in expressing ABSOLUTE POWER limits, for example, as shown in Table 25-C: Operational bands: edges, status, power, restrictions on page 343. Decibel, on its own, describes a ratio, that is, how much stronger (or weaker) something is. Because it is relative and not absolute, it could not be used, on its own, to express a power limit in watts. However, decibel can be combined with the reference (base) power level of 1 W to create a new unit called DECIBEL-WATT, or **dBW**. It expresses dB relative to 1 W and it is used extensively in radio.

It is simply a value, in dB, that tells you how many times the power of interest is higher (or smaller) than 1 W. For example, 0 dBW would mean 1 W, because 0 dB means a ratio of 1 and 1 × 1 = 1. 10 dBW would be 10 × 1 W = 10 W, and so on. You need to know the following power levels expressed as dBW, because they appear frequently in Irish radio regulations.[149]

Table 9-B: Power in watts as dBW

dBW	**W**
10 dBW	10 W
12 dBW	15 W
14 dBW	25 W
17 dBW	50 W
20 dBW	100 W
26 dBW	400 W
30 dBW	1 kW
32 dBW	1.5 kW

This technique can be used with other base power levels, not only 1 W. Many weak transmission modes, such as Weak Signal Propagation Reporter (WSPR) express power in dBm which stands for decibel-milliwatt.[150]

149 The formula to convert any other value of dBW to W is $W = 10^{dBW/10}$. For example, 28 dBW in W? $10^{28/10} = 10^{2.8} = 630.95\ W$. You would need to use a calculator that has a function of raising 10 to the power of an arbitrary number. How to convert W back to dBW? dBW = $10 \log_{10}$ W. For example: $10 \log_{10} 630 = 10 \times\ 2.79 = 27.9 \approx 28$ dBW. You do not need to know these formulas for the exam.

150 For example: 0 dBm = 1 mW, 10 dBm = 10 mW, and 30 dBm = 1 000 mW = 1 W. When using WSPR you will often see the power expressed this way. dBm is also sometimes written as dBmW.

9.4 Effective Power

Calculating effective power is easy in decibels. EFFECTIVE POWER is the power at the end of a chain of several devices which, each in turn, increase or decrease the input power. To calculate it you need to add the output power of a transmitter, in dBW, together with all the decibel power increases or decreases caused by each device.

For example, let's find out the effective power of a transmitter that outputs 100 W into a coaxial cable that has a loss of 1 dB and an antenna that has a gain of 7 dBi.[151] First, we find the dBW value of 100 W in Table 9-B. It is 20 dBW. Then, we add them together, and finally convert the result in dBW back to W, using the table, if needed.

$$20\text{ dBW} - 1\text{ dB} + 7\text{ dBi} = 26\text{ dBW} = 400\text{ W (EIRP)}$$

We have just calculated the Effective Isotropic Radiated Power (EIRP), which is similar to Effective Radiated Power (ERP) . It will be discussed in more detail in section 15.20 Effective Power: EIRP and ERP.

151 dBi and dBd and their relationship to EIRP and ERP will be explained in section 15.15 Directivity, Efficiency, and Gain. For now, assume that a dBi is equivalent to a dB in the context of effective power.

10 Other Components and Circuits

THREE EXAM QUESTIONS · SECTION A4

The components and the circuits discussed in this chapter are used in all radio electronics. Unlike resonant components and circuits, discussed in Chapter 8, these components are somewhat simpler to understand on their own. However, they can be used to build intricate devices, especially in conjunction with their resonant siblings.

10.1 Diodes

Diodes belong to a group of electrical components known as semiconductors,[152] see section 3.3.3 Semiconductors and Solid-state Electronics. There are two types of semiconductors that are used to make a diode: n-type and p-type, negative and positive. Diodes are constructed by joining together these two types of semiconductor material, creating a single semiconducting junction. Diodes have two terminals (ends) that are attached to each of the two semiconducting components.

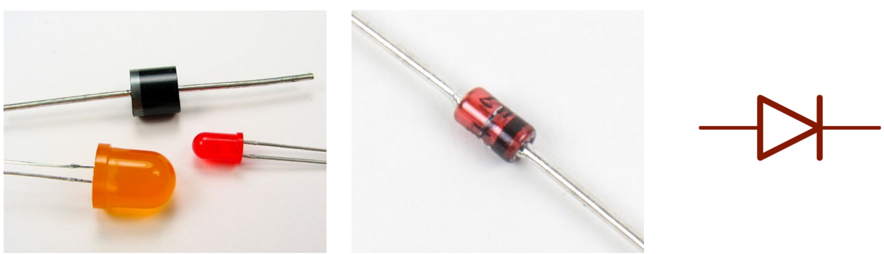


Figure 10-i: Diodes. Left rear: rectifying (power) diode. Left centre and front: two light-emitting diodes (LEDs). Centre: Zener diode. Right: Symbol of a diode.
[Images by Windell Oskay, see page 375. Symbol by EI9ILB.]

As a result of this construction, a diode sometimes passes the current through it, and sometimes it does not. Whether a diode behaves like a conductor, or an insulator depends on the direction of the current trying to pass through the diode. The symbol of a diode, shown below, looks like an arrowhead. It denotes the conventional flow direction in which the current must be flowing for the diode to conduct it.[153] You can think of a diode as a valve that opens to let the current through only if a sufficient voltage has been applied in the correct direction, but which does not let the current in the opposite direction.

There are several different types of diodes. Rectifying diodes, also known as power diodes, are often used in power supply units to convert, or rectify, AC into

152 Historically, thermionic diodes existed long before semiconductor diodes, which are the type currently in use. See section 10.3 Valves (Thermionic Devices).
153 Recall that the conventional direction is from positive to negative terminal, however, electrons flow in the opposite direction. See section 3.3.1 Electricity & Current.

DC. You will see an example of that in section 10.6. ZENER DIODES are used to set and stabilise the output voltage of power supplies. LIGHT EMITTING DIODES, LED, are now a very popular source of household lighting, but they are also used in instrument displays, and for more specialised uses, such as lasers. PHOTODIODES are sensitive to light, and they let the current pass when they are exposed to sufficient light. In line with the exam syllabus, this section focuses on the most basic type of a diode, the rectifying diode, however all diodes share common characteristics.

10.1.1 Forward Voltage (Bias Voltage)

Before a diode turns on and behaves like a conductor it requires a minimum voltage to be applied to its terminals in the correct direction, which is indicated by the arrow shape of its schematic. This minimum voltage is different depending on the material used to make the diode. For silicon diodes this FORWARD VOLTAGE, also known as BIAS VOLTAGE, is between 0.6–0.7 V (600–700 mV).

When using a rectifying diode in a circuit the remainder of the circuit will experience a reduction in the voltage equal to that forward voltage of 0.6–0.7 V. This voltage reduction is often referred to as the diode's VOLTAGE DROP.

10.1.2 Peak Inverse Voltage

The PEAK INVERSE VOLTAGE, PIV, is the highest voltage that can be applied to the diode in the opposite direction to the diode's conducting direction. If PIV is exceeded, the diode will break down, and it will allow the current to flow back through the diode, against its design direction. Unfortunately, this will usually damage the diode and it will allow the current to flow in both directions.

10.1.3 Leakage Current

Although the diode is supposed to conduct current only in one direction, there is a very small amount of current that would be allowed to flow back through the diode in the opposite direction if the voltage was applied to it that way. This amount of current is called LEAKAGE CURRENT. It varies depending on the material from which the diode was made. The amount of leakage current is very small in a rectifying diode. However, you should be aware of it because it cannot be assumed that a diode behaves like a perfect insulator in the non-conducting direction. This can be important for some types of circuits.

10.1.4 Power Rating

Diodes, like resistors, other electrical devices, and all other semiconductor components including transistors, can only handle a finite amount of power. They have a MAXIMUM POWER RATING which must be considered when choosing which component to use in a particular circuit.

10.2 Transistors

Like diodes, TRANSISTORS are also members of the semiconductor family of electronic components which were introduced in section 3.3.3. They are considered the most important member of the semiconductor family, and the foundation of solid-state electronics.

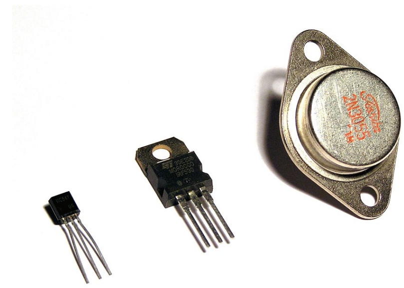


Figure 10-ii: Transistors.
[Image by Mumin 123, see page 375]

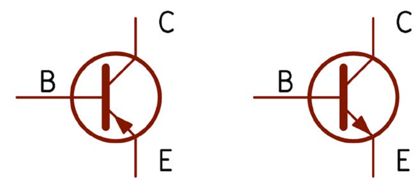


Figure 10-iii: PNP (left) and NPN (right) bipolar junction transistors (BJT) symbols. [EI9ILB]

There are many types of transistors. The most traditional one, and the one that you need to study in some detail is known as a BIPOLAR JUNCTION TRANSISTOR (BJT)

Semiconductors are made from n-type and p-type materials which, when placed next to each other, form a semiconducting junction. While a diode, explained in the previous section, had just one semiconducting junction, a bipolar transistor has two such junctions. Depending on the order in which the n-type and p-type materials have been joined together, a bipolar transistor will be either an NPN or a PNP transistor.

A bipolar transistor has three terminals (ends) which are connected to each of the three components from which it was made. Those three terminals are known as the BASE, COLLECTOR, and the EMITTER. In a schematic symbol of a transistor, shown in Figure 10-iii, the arrow on the emitter denotes which way the current would flow, much as it does in the schematic symbol of a diode.[154]

10.2.1 Currents and Biasing in a BJT

It is useful to understand how a BJT works. Without a voltage between the base and the emitter of a transistor, no current can flow between the collector and the emitter terminals. Like a diode, when a small voltage of between 0.6–0.7 V (for a silicon transistor) is applied between the base and the emitter, it has the effect of *turning on* the transistor. The level of bias voltage determines when the transistor turns on. This is known as BIASING. It is useful for designing different classes of amplifiers, which will be discussed in section 10.7.3 Biasing.

When it turns on, the transistor will allow a larger current to flow between the collector and the emitter terminals. It will have two separate currents flowing through it at the same time.[155] One current, known as the BASE CURRENT I_B, flows

154 An easy way to identify the transistor from its symbol uses a handy mnemonic of *not pointing in* or *never points in,* meaning that on an NPN transistor the arrow never points towards the centre.

155 It is common in electrical circuits to have several different currents, often with different voltages, all flowing through a shared connection or a wire at the same time.

between the base and the emitter. The other current, the COLLECTOR CURRENT I_C, flows between the collector and the emitter, see Figure 10-iv. The flow of this current is controlled by the flow of the base current. The emitter is carrying the current I_E that is the sum of the two other currents:

$$I_E = I_C + I_B$$

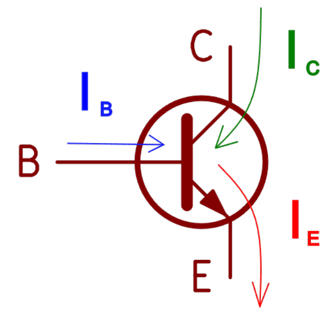


Figure 10-iv: Current flows in a BJT [EI9ILB]

Transistors can be connected in different ways in a circuit. By sharing one of its three terminals with other parts of the circuit it is possible to take advantage of different current flows to cater for different signal processing designs. You may want to learn more about some typical approaches, including common emitter, common base, and common collector.

10.2.2 Amplification Factor

One the most important uses of a transistor is to act as an amplifier: a device that increases the strength (current, voltage, and power) of an AC signal, at either audio or radio frequencies.[156] This is possible, because a small base current can control a much larger collector current. The small current represents the signal to be amplified. The larger current that is supplied to the transistor from a more powerful voltage source becomes the amplified signal once its waveform is made to match the waveform of the smaller signal. Transistor provides this means of control: allowing the waveform of the smaller signal to shape the large signal. Amplifiers will be discussed in section 10.7.

The ratio of the larger collector current to the smaller base current is known as the AMPLIFICATION FACTOR, or as the TRANSISTOR GAIN. It is denoted by the Greek letter β (beta). It can be a ratio of many hundreds of times.

In addition to being used as a building block of amplifiers, a BJT can also be used as an on-off switch, controlled by the application of current to its base.

10.2.3 BJT vs FET

There are other types of transistors, including a FIELD EFFECT TRANSISTOR, FET. The main difference between BJT and FET is how they are controlled. BJT uses base current to control the collector current. FET uses small changes to voltage to control

156 Transistors were invented for the purpose of signal amplification in 1947 by American physicists John Bardeen and Walter Brattain while working for William Shockley at Bell Labs. They have received a Nobel prize in 1956 for their work. Prior to transistors, amplifiers used valves – delicate, with a limited lifespan, and inefficient. The transistor started the electronic era that continues today. They are fundamental to all electronics and computing. Every computer chip has many of them. A mid-range Intel Xeon microprocessor has over 8 billion transistors, while a recent Apple M2 Ultra chip has 134 *billion* transistors on a single silicon chip not much larger than a postage stamp.

larger currents. There are other differences between them, including their symbols and terminology, however, you are not required to study those.

10.3 Valves (Thermionic Devices)

Valves, also known as thermionic devices, electronic valves, or vacuum tubes, were the predecessors of transistors and solid-state electronics. They fulfilled the original requirement of signal amplification and made long-distance communication possible.[157]

Figure 10-v: Valves. Left: triode, centre: power triode with a heat sink, used in RF transmitters, right: voltage regulator tube, functionally similar to a Zener diode.
[Images, from left, by: joseteo2, Hannes Grobe, VA7IS, see page 375]

Basic electronic valves can perform a function of a diode or a transistor. They can also amplify AC and they can act as high-speed switches. Some valves have more intricate designs that improve their basic function, or that can function like several connected transistors, or even as more complex circuits.

A valve is a container made of glass or ceramics. The air has been removed from it, creating vacuum, which is usually replaced with a special gas.

10.3.1 Triode

Triode is a valve that is closest in its function to a FET transistor, see 10.2.2. Inside its glass container there are four elements.

157 Valves were invented in 1904 by John Ambrose Fleming, an English electrical engineer and physicist. The very first valve, known as a Fleming valve, was a diode, used to demodulate radio transmissions.

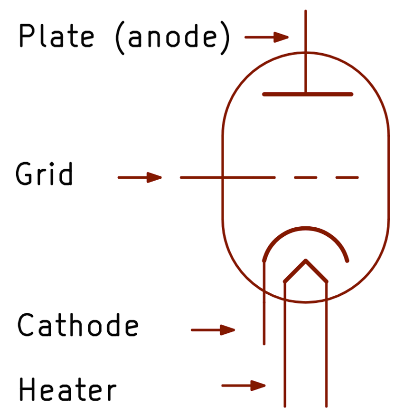


Figure 10-vi: Triode symbol. [EI9ILB]

1 HEATER ELEMENT (FILAMENT) conducts a current and gets very hot.
2 CATHODE is close to the heater. When hot, the cathode emits electrons into the vacuum, rather like steam rising from boiling water. This is called *thermionic emission.*
3 ANODE (also known as PLATE) is close to the cathode. When voltage is applied between the cathode and the anode, the emitted electrons become attracted to the anode and move towards it, while more electrons are replenishing the cathode from the connected supply. This flow of electrons through the space between the cathode and the anode can represent a very large current. An external circuit is normally connected to carry it as necessary, for example towards the transmitting antenna that may require the considerable power produced by the triode.
4 CONTROL GRID, made of a metal mesh, placed between the cathode and the anode. The electrons travelling from the cathode to the anode can pass through the holes in the mesh. However, if voltage is applied to the grid the flow of the electrons can be gradually reduced or even stopped altogether.

By applying a small, varying voltage to the grid, the triode controls a large current flowing between the cathode and the anode, similar to how an FET works. As a result, the triode acts as an *amplifier.* The voltage applied to the grid represents the signal to be amplified. The stronger, amplified signal flows as the current between the cathode and the anode.

Although valves are an old technology, which has been generally superseded by transistors, they still have some uses in radio. One of their advantages is that they are less affected by mismatched load impedance than solid state electronics, see section 14.9 Impedance Matching and Transformation. Perhaps more importantly, as an amplifier, they can provide very high levels of power relatively inexpensively.[158]

10.3.2 Valve Safety

To enable the electrons to travel through the space between the cathode and the anode valves must use very high voltages. Thousands of volts and high currents make for a lethal combination. People have, unfortunately, died from serious electric shocks this way.

158 Their ability to handle high power levels at a reasonable price is one of the reasons why they are still used for high-power RF signal amplifiers. The price of commonly used valves ranges €50–400, which compares well to equivalent transistors costing €200-600. However, valves have a limited lifespan and require replacement after a few hundred or a couple of thousand hours of use.

! Never work on an open valve transmitter, amplifier, or another device that contains valves without taking precautions. Even if the device has been turned off, make sure to fully discharge the capacitors in such a device, as they may hold a high voltage for a long time, months or even years. See also section 19.4.5 Valve Equipment and High Voltage Power Supplies.

10.4 Integrated Circuits

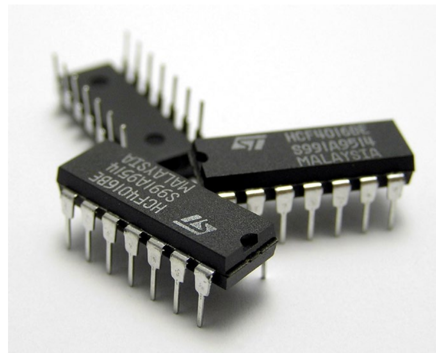


Figure 10-vii: Integrated circuits.
[Image by Kimmo Palosaari, see page 375]

An INTEGRATED CIRCUIT, IC, is a small device that contains multiple electronic components. They can include transistors, diodes, resistors, capacitors, inductors etc. Those components are so small, that a single IC can contain even billions of components. They are permanently connected to an internal circuit, and they are encased in a hard plastic or ceramic coating. An IC can perform many functions and it can even be a complete electronic device.

ICs have multiple terminals (ends) allowing them to be connected to external circuits or various controls, such as switches, potentiometers, or other input-output devices. There are two general types of ICs:

- DIGITAL IC. Logic gates, counters, microprocessors, DSP processors, ADCs and DACs, NCOs, and many others.[159] Digital ICs, especially those used in computers, are often referred to as CHIPS, or computer chips. A basic SDR receiver can comprise of a single digital IC mounted on a USB stick.
- ANALOGUE IC. Amplifiers, mixers, voltage regulators, complete radio receivers and other devices. These more traditional ICs are also sometimes referred to as linear ICs.

159 See Chapter 6 Digital Signal Processing and Non-Sinusoidal Signals for more information on DSP, ADC, DAC, and NCO. There are many other types of digital integrated circuits, however, you are not required to know them. One other IC that you may hear about is an FPGA, a Field Programmable Gate Array. It functions like a customisable microprocessor. Some of the SDR radios use FPGAs to perform sampling and frequency down-conversion functions. It is cheaper for a radio manufacturer to program an FPGA than to design and manufacture a bespoke microprocessor.

10.5 Transformers

A TRANSFORMER is an electrical device that transfers electrical energy from one circuit to another while changing, or transforming its voltage, current, or impedance. They are used extensively, especially in everyday devices, including computer power supplies and mobile phone chargers. Common household transformers transform mains supply 230 V to something lower, like 5 V, 12 V, or 13.8 V that is often used with radio equipment.

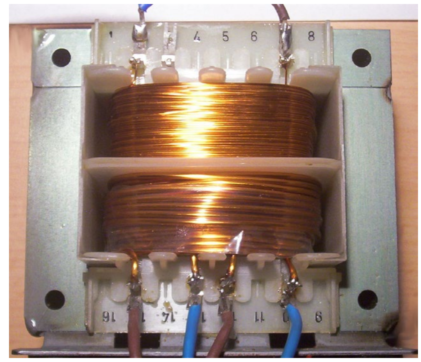


Figure 10-viii: Transformer. 230 V on the primary winding (top) to two 9 V secondary windings (bottom).
[Image by Stefan Riepl (Quark48). See page 375]

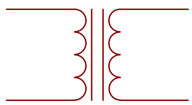


Figure 10-ix: Transformer symbol. [EI9ILB]

10.5.1 Principle of Operation

A basic transformer contains two coils (inductors) placed close to each other. If AC is passed through one of the coils the magnetic field produced by that current will pass through the second coil.[160] Because the current in the first coil is constantly changing its direction, its magnetic field is also varying. This constant changing of the magnetic field induces a varying electromotive force (emf) in the second coil, and, as a result, AC flows in the second coil if it is connected to a circuit.

Please note, that transformers only work with AC. A non-varying DC would not create the necessary magnetic field for a transformer to work, except at the brief moment when it is turned on or off.

10.5.2 Transformer Characteristics

The two coils of a transformer are normally referred to as a PRIMARY and a SECONDARY WINDING. The number of times a wire has been coiled, i.e., the number of its TURNS in each winding, is an important characteristic of a transformer.

If the primary winding has more turns of the wire than the secondary winding, then the voltage on the secondary winding would be proportionately lower. For example, if a primary winding has 100 turns and it is supplied with 200 V AC, and the secondary winding has 20 turns, then it will produce a voltage of 40 V AC. Because the secondary winding has only one fifth of the number of turns it only produces one

160 To be precise, the varying current in one coil produces a varying magnetic *flux* in the transformer's core. Magnetic flux describes a magnetic field on a given surface. Only iron-core transformer are discussed in this section, but air, ferrite, and other cores can be used to change how the magnetic flux passes between the windings. Ferrite cores are particularly useful in RF impedance transformers.

fifth of the voltage. Such a transformer would be called a STEP-DOWN TRANSFORMER because it reduces the voltage. If the transformer had a primary winding with fewer turns than on its secondary winding it would be a STEP-UP TRANSFORMER: it would increase the voltage.

If the primary and secondary windings have the same number of turns then the voltage, current, and impedance will be the same on the circuits connected to both windings. Such a transformer is known as an ISOLATION TRANSFORMER because although the two circuits are not physically connected to each other it can pass AC from one to the other. An isolation transformer can be used to provide additional safety when working on live circuits because it isolates the mains neutral, and its path to the ground, from the secondary winding's AC circuit. If used correctly, this can prevent some types of accidents in which current would otherwise pass through the human body to the ground.

Nothing is gained in a transformer without losing something else. When a transformer increases a voltage, it proportionately decreases the current going through the secondary windings, and the other way round.

Transformers also transform impedances of the circuits connected to them. This characteristic is used to match impedances of antennas and transmission lines to transceivers. IMPEDANCE TRANSFORMERS are discussed in section 14.11 Baluns and Chokes.

The ratio of the number of turns of the wire on each winding is known as the TURNS RATIO. Table 10-A shows the relationship between voltages, currents, and impedances of a transformer whose primary winding has N_{pri} turns of the wire, and the secondary winding has N_{sec} turns.

Notice that the voltage ratio is the same as the turns ratio, while the current is the inverse.

Table 10-A: Transformer characteristics and turns ratio

Ratio	Relationship to turns ratio
Voltage Ratio	$\frac{V_{sec}}{V_{pri}} = \frac{N_{sec}}{N_{pri}}$
Current Ratio	$\frac{I_{sec}}{I_{pri}} = \frac{N_{pri}}{N_{sec}}$
Impedance Ratio	$\frac{Z_{sec}}{Z_{pri}} = \left(\frac{N_{sec}}{N_{pri}}\right)^2$

Figure 10-x shows the characteristics of a transformer with a 10:1 turns ratio, for example, one that has 100 turns on the primary (left) and 10 turns on the secondary (right) winding. Assuming the circuit connected to the primary winding is supplying AC with 50 V, 10 mA, and 5 kΩ impedance, the secondary winding circuit will have a lower voltage, higher current, and a much lower impedance. The secondary winding will have 5 V, 100 mA, and 50 Ω.

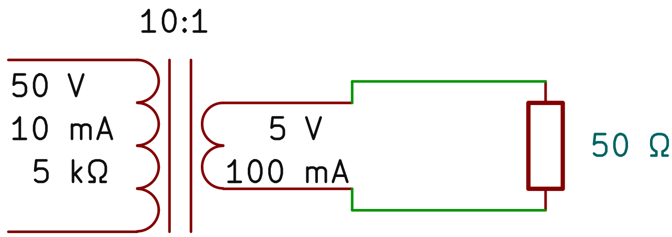


Figure 10-x: Example of a transformer with a 10:1 turns ratio and its effect on voltage, current, and impedance. [EI9ILB]

Unfortunately, in a real transformer some of the energy will be lost in the process because no transformer is perfect. Typically, about 5% of the applied power is lost, primarily as heat.

10.6 Power Supplies

A POWER SUPPLY, also known as a Power Supply Unit (PSU) is a complete circuit consisting of several electrical devices. It is used to convert source electricity to a stable current that has the desired voltage, current, and frequency.

Power supplies commonly used in amateur radio installations convert mains supply 230 V AC to 13.5 V DC that is required by many commercially available transceivers. Such a power supply implements its function by combining three technologies.

1 Voltage transformer, or a switched mode power supply, to reduce the mains voltage.
2 Rectifier to convert AC to DC.
3 Voltage regulator, also known as a stabiliser, to keep the DC voltage from changing even if the source varies.

Figure 10-xi: Power supplies, linear, 230 V AC to 13.5 V DC, max 7 A (top), max 35 A (bottom). [EI6LA]

10.6.1 Voltage Transformer

A simple and a long-established way of changing voltage uses a transformer. To reduce the mains voltage, a step-down transformer is necessary, see section 10.5. In a power supply, it is also referred to as a VOLTAGE TRANSFORMER.

Power supplies that rely only on a transformer to change the voltage are sometimes known as LINEAR POWER SUPPLIES. If they are designed to supply considerable

currents, such as 20 A or more, whilst operating at 50 Hz mains frequency, they are heavy and bulky because of the size and weight of the necessary transformers.[161]

10.6.2 Switched Mode Power Supply

Instead of using one large bulky transformer, voltage can be reduced in another way. The size and weight of a transformer depends on the frequency of its operation. Lower frequencies require bigger transformers than higher ones. In a SWITCHED MODE POWER SUPPLY the mains source is used to directly drive an oscillator to produce the same voltage, but at a much higher frequency, even up to 200 kHz. The higher frequency source voltage is then reduced using a much smaller and lighter transformer than would be required if operating at 50 Hz. The transformed higher frequency voltage is then rectified and regulated using also much smaller and lighter components.

Switched mode power supplies can be highly efficient and light, but they are also often a source of Electromagnetic Compatibility (EMC) problems due to the oscillator's harmonics generating RF noise if not properly filtered and shielded. Because of their smaller size these power supplies may also require potentially loud cooling fans if operating at higher currents.

When diagnosing sources of any excessive RF *noise* in your station, consider any non-linear power supplies, especially the small, switched mode power supplies that come with almost all consumer electronics. Together with built-in and standalone LED light power supplies, those are the main sources of nearby RF noise.

10.6.3 Rectifier

RECTIFICATION is the process of transforming AC to DC. There are many ways how this can be accomplished, however, only two approaches need to be studied: half-wave and a full-wave rectification.

10.6.3.1 *Diode: Half-wave Rectification*

The simplest way to rectify AC is to pass it through a single rectifying diode (power diode). As long as the diode is used within its design parameters, it only passes the current that flows in one direction. Figure 10-xii shows a circuit consisting of a transformer connected to a power diode. The load being supplied is represented by the resistor on the right.

161 Transforming 230 V to 13.5 V while allowing for larger currents required by modern transceivers, such as 30 A, requires a transformer weighing a few kilograms. To dissipate the heat, it would also need a fan or heavy and also bulky radiator. However, despite the size, weight, and heat, linear power supplies are good for radio purposes because they do not generate RF noise associated with cheaper switched mode power supplies.

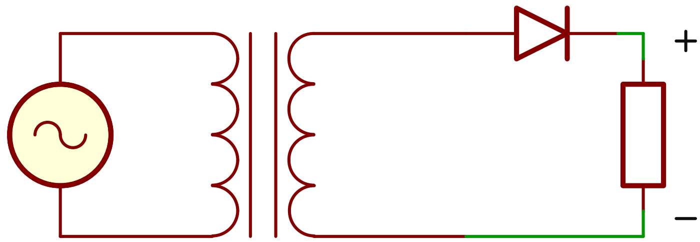


Figure 10-xii: Half-wave rectifier. [EI9ILB]

The output from this circuit, is DC but its voltage is not stable. Even though it flows in one direction only, the current and voltage vary at the frequency of the source. During each half-period of the source's AC there is no voltage on the output of this circuit, because at those times the power diode is not conducting. This is the reason why this form of producing DC from AC is named HALF-WAVE RECTIFICATION. It is shown in Figure 10-xiii.

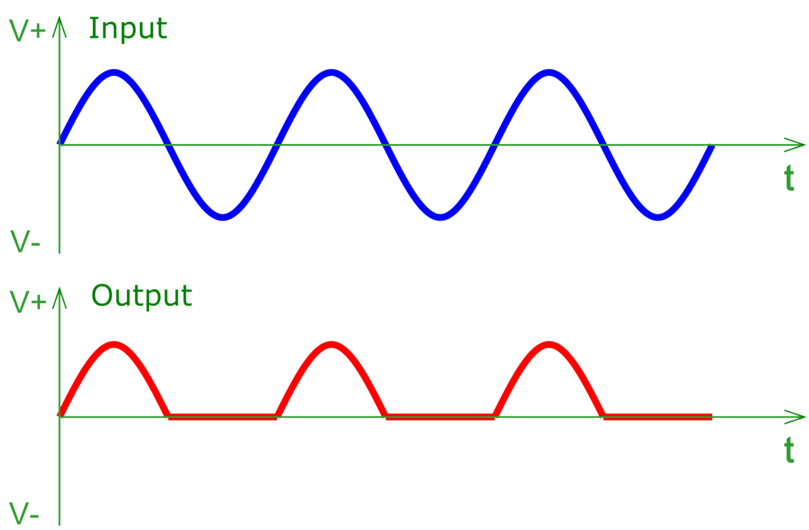


Figure 10-xiii: Half-wave rectification. [EI9ILB]

To improve the output voltage, a SMOOTHING CAPACITOR is usually added at the output of the power supply's circuit. The capacitor charges during the half-wave periods when the current passes through the diode, and discharges when no current flows through the diode, providing a top-up flow of current that has the effect of smoothing the changes of the voltage. Unfortunately, even that will not produce perfectly smooth and stable DC, there will be still a trace of the source frequency in it. However, this might not matter for some types of loads.

10.6.3.2 *Bridge Rectifier: Full-wave Rectification*

A circuit consisting of four power diodes, shown in Figure 10-xiv, is known as a bridge rectifier.

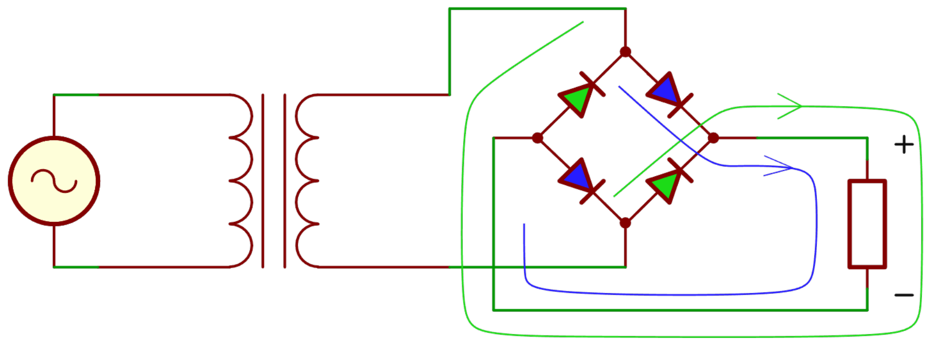


Figure 10-xiv: Bridge rectifier. Green and blue lines show the direction of the current flow during each of the two half-cycles of AC. [EI9ILB]

Unlike a half-wave rectifier, BRIDGE RECTIFIER outputs current during both half-periods of the source AC. This can be seen in Figure 10-xv.

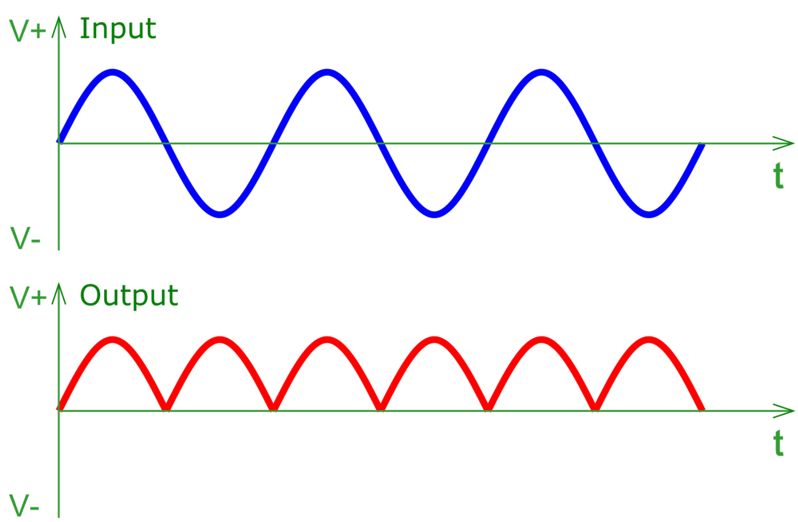


Figure 10-xv: Full-wave rectification. [EI9ILB]

Output from a bridge rectifier still requires the use of a smoothing capacitor to produce voltage that is not varying too much and is closer to an ideal, stable DC. It is shown in Figure 10-xvi. The smoothed voltage is shown in Figure 10-xvii.

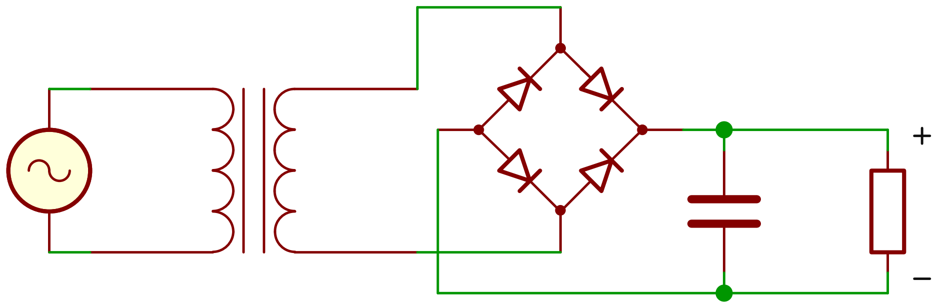


Figure 10-xvi: Bridge rectifier with a smoothing capacitor. [EI9ILB]

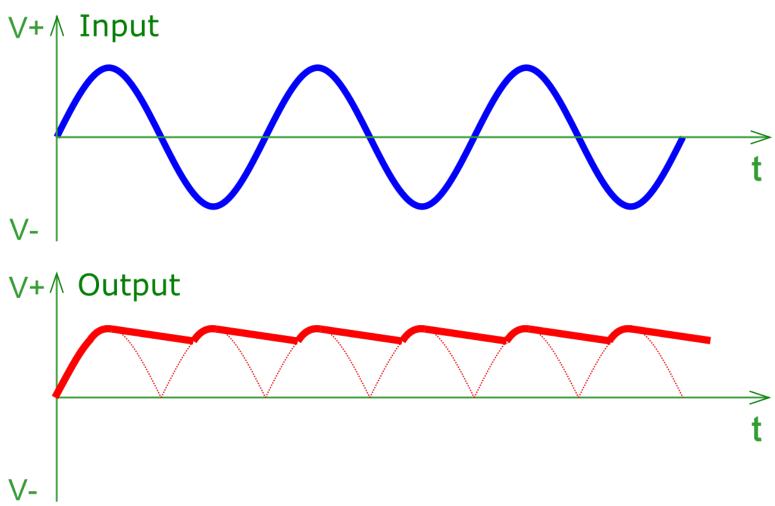


Figure 10-xvii: Full-wave rectification with smoothing. [EI9ILB]

10.6.4 Voltage Regulator (Stabiliser)

A disadvantage of the transformer is that the output voltage will vary if the source varies. To achieve stable output voltage additional circuits are required. VOLTAGE REGULATORS, also known as VOLTAGE STABILISERS, can be built from a combination of transistors and Zener diodes. Ready-made integrated circuits are available to perform the voltage stabilisation functions.

Overall, a power supply can be very simple or surprisingly complex, especially if one requires it to provide a stable voltage and current, produce no RF noise, and to operate quietly without generating too much heat.

10.7 Amplifiers

Power amplifiers are electronic devices or circuits used to increase the power of a signal applied to their inputs. They are widely used, both as large, standalone devices, and as small, even miniature components of other circuits.

There are amplifiers that amplify only the current, or only the voltage, and those that amplify both current and voltage. Power, in turn, depends both on voltage and current – see section 3.10 Electric Power and Energy. You only need to study power amplifiers for the exam, without needing to know the differences between voltage and current amplifiers. This guide uses the terms *amplifier* and *power amplifiers* as synonyms of each other.

Both AF and RF amplifiers are used in radio. Amplification of audio frequency signals has different requirements than amplification of radio frequencies. As a result, there are different designs for both applications.

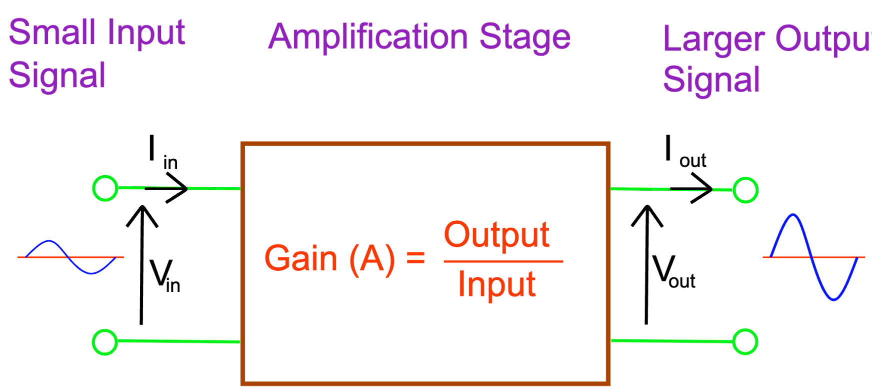


Figure 10-xviii: Signal amplification. [EI9ILB]

10.7.1 Amplifier Characteristics

Amplifiers have six important characteristics.

1 POWER GAIN describes the ratio of the power of the amplified output signal to the power of the input signal. For example, an amplifier that is fed with 10 W of power that outputs 1 000 W of power would have a gain of 100. Ratios are commonly expressed in decibels, see Chapter 9. This example amplifier's power gain would be 20 dB. Bear in mind that the power gain ratio is not identical to the ratios of output voltage or current. However, voltage gain, and current gain can be easily converted to power gain. This requires some care, because for the same amplifier its power gain, in decibels, will be different from its voltage or current gains expressed in decibels. See section 9.2.2 Power Ratios using Voltage or Current as Decibels.

2 LINEARITY is a highly desirable quality of amplifiers used in radio. It means that the power gain of the amplifier remains constant and does not depend on the power of the input signal. An amplifier that would amplify signals of different powers

differently, with an uneven gain, would be non-linear. It would distort the signal, making it harder or even impossible to read the amplified signal in case of a significant non-linearity. However, while no amplifier is perfectly linear, there are some applications that can cope with poorer linearity, especially if such an amplifier offers other advantages, such as cost or efficiency.

3 OUTPUT POWER of an amplifier determines the maximum power it can deliver. By knowing the gain of an amplifier, you can calculate the maximum drive level, that is, the maximum power of the input signal that can be fed so that the amplifier does not exceed its output power rating. Exceeding this parameter is known as overdriving the amplifier. This will have many negative effects, discussed below.

4 FREQUENCY RANGE determines if the amplifier can be used for AF or RF. Further, RF amplifiers have a limited range of frequencies they can amplify. For example, HF amplifiers may not be able to amplify VHF or UHF signals.

5 STABILITY means that the amplifier output accurately maintains the frequency of the input signal without adding its own, unwanted oscillations to it.

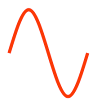
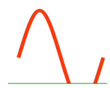
6 EFFICIENCY is a ratio of total power that is consumed by the amplifier to produce the required output power. Total power includes the power of the input signal that is being amplified, which is usually small, and the much larger power consumed from the amplifier's power supply. Amplifiers are generally not very efficient devices, and a large amount of the supplied power will be lost to generate heat during amplification. In some amplifiers half of the supplied power is wasted as heat just to output the other half as the amplified signal.

10.7.2 Classes of Power Amplifiers

Power amplifiers have a class code designation, such as A, AB, B, or C. Those CLASSES describe many of their characteristics.[162] The main difference between the classes is how the output signal waveform differs from the input signal. While only class A amplifier produces an output wave that is identical to the input, the remaining classes have many practical uses, even class C, whose linearity is very poor.

162 There are more classes: D, E, F… They are *non-linear* and use *switched mode* amplification principles. They are very efficient, close to 100%, however, their non-linearity greatly limits their applications.

Table 10-B: Power amplifier classes and their characteristics

Class	Output waveform	Efficiency	Advantages	Disadvantages
A	Full 	25-30%	No distortion or negligible distortion Simple design Best linearity	Inefficient Generates much heat High cost or low durability
AB	Almost full 	50-60%	Good efficiency Minor harmonic distortion Good linearity	High cost
B	Half 	65%	Good efficiency Low cost Acceptable linearity	Increased distortion may be unacceptable for AF
C	Less than half 	80%	Best efficiency Lowest cost	High distortion Poor linearity

10.7.3 Biasing

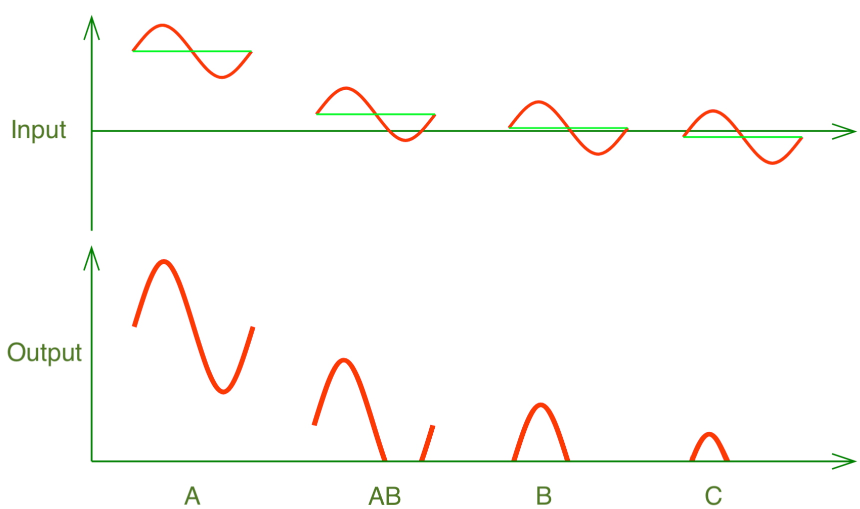


Figure 10-xix: Power amplifier classes and biasing. [EI9ILB]

Amplifier classes can be implemented in different ways. A common approach uses the principle of biasing, see section 10.2.1 Currents and Biasing in a BJT. To bias a

transistor, just like to bias a diode, a small amount of voltage must be applied to it before it starts to conduct the current.

By adding a carefully chosen level of BIAS VOLTAGE to the input signal, class A amplifier's transistor or valve will conduct for the full cycle, class AB for part of the cycle, class B for half of the cycle, and class C for less than half of the cycle of the input signal. This is illustrated in Figure 10-xix. Notice how the input waveform, shown on top, has been shifted up by the different amounts of bias voltage, and how that has affected the shape of the resulting output waveform, shown on the bottom.

In addition to biasing, different amplifier classes use other techniques, such as using pairs or multiples of transistors, and further circuitry, to improve the efficiency and linearity, and to reduce the distortions that an amplifier generates. Since all classes other than A offer efficiency gains for the price of some acceptable non-linearity, amplifier design must achieve efficiency while delivering maximum undistorted output power to the transmission line and the antenna. This requires making some interesting compromises, notably involving their output impedance. This is discussed in sections 12.3 Output Impedance and 12.4 Efficiency and Output Power.

10.7.4 Distortion from Amplifier Non-Linearity

Distortion in an amplifier is usually caused by its non-linearity. Every amplifier, including all linear amplifiers, have some non-linearity. That non-linearity dramatically increases when the amplifier is OVERDRIVEN, that is, when it is fed with input signal power that would make it exceed its rated maximum output power. Even if the overdriven amplifier turns on a protective circuit, such as Automatic Level Control (ALC), the output will be distorted, because the stronger parts of the input signal are amplified less than the weaker ones. Unless carefully implemented, ALC can make distortion worse. The resulting signal might not represent the original one anymore.

All transceivers have internal amplifiers. Distortion can be caused within a transceiver, even if you do not use an external amplifier. There are two main types of distortion caused by amplifier non-linearity.

1. HARMONIC DISTORTION causes otherwise insignificant replicas of the input signal to be amplified much more than the original signal itself causing significant interference with both nearby frequencies, as well as frequencies on different bands.
2. INTERMODULATION DISTORTION (IMD) causes unwanted signal mixing byproducts to be amplified more than the original signal, distorting audio, or causing loss of data in a digital signal.

These types of distortion and the harmful interference that they cause are explained in detail in section 18.2 Transmitter Distortion and Spurious Emissions. Never overdrive an internal or an external amplifier. Not only does it cause distortion,

but it also shortens its life. It can cause it to fail suddenly, requiring a replacement of the expensive final amplification stage transistors, valves, or other components.[163]

10.7.5 AF Amplifiers

AF POWER AMPLIFIERS increase the power of inaudible audio signal to the level required to be heard over a speaker or a headset. Essentially, they increase the volume of the audio that you hear. AF power amplifiers need to work with only a narrow range of audible frequencies. Even though a perfect human ear is capable of hearing sounds up to 20 kHz, AF amplifiers used in radio are only required to amplify audio signals in the human voice range, approximately 300 Hz–3 kHz. This makes their design simpler than is required for music HI-FI (High Fidelity) AF amplifiers used to listen to music. At the same time, amplification of voice signal requires a very low level of distortion, which is why class A or AB power amplifiers are usually used for AF purposes.

10.7.6 RF Amplifiers

Figure 10-xx: Standalone 1 kW power amplifier for 1.8–54 MHz. [Image by Linear Amp UK, see page 375]

RF POWER AMPLIFIERS convert a weak radio signal into a more powerful signal. They are a component of all common receivers and transmitters. In a receiver, they amplify the weak signal received by the antenna so that it can be demodulated, see Chapter 13 Receivers. In a transmitter, they amplify the just-created RF signal to a level of power that is required for a successful transmission, see Chapter 12 Transmitters. All transceivers contain internal RF power amplifiers, sometimes more than one. However, it is also possible to use external RF power amplifiers to further increase the power of the transmitted signal.

RF power amplifiers must work with a much broader, and higher range of signal frequencies than AF, because the RF spectrum ranges from 3 kHz to 3 000 GHz (3 THz). RF power amplifiers are designed to work only with sections of that spectrum. For example, a commercial power amplifier may be designed to work with the MF and HF range of 1–30 MHz, while another one may also cover some of the VHF at 50–70 MHz, and yet another would only cover VHF or UHF.

163 The transistors or valves that perform the final stage of amplification, also known as the *finals,* are the most important components of an amplifier. They perform the hardest duty by offering the highest power gain. Because they must tolerate large amounts of power and high heat, whilst remaining precise and stable, they are expensive. If they are overdriven with excess input power, or affected by the distortion artefacts, they eventually burn out.

Common RF power amplifier classes are AB and B, however, even class C is appropriate for some purposes, such as amplification of FM and many digital signals such as CW (Morse code), RTTY, and the more modern modes, such as WSPR and FT8. Those modern digital modes, however, require the amplifier to be relatively free of intermodulation distortion (IMD).

Output impedance of RF amplifiers has an interesting relationship to its efficiency. It is discussed in more detail in sections 12.3 Output Impedance and 12.4 Efficiency and Output Power.

11 Modulation and Modes

EIGHT EXAM QUESTIONS · SECTIONS A3 A5

Radio is a versatile, reliable, and an economical way to have simultaneous transmissions of information anywhere around the world and the universe. To allow a great number of transmissions not to interfere with each other, an unused carrier frequency must be selected for each transmission. As explained in Chapter 25 Radio Spectrum Allocation in Ireland and IARU Band Plans, that frequency must also belong to a band plan allocated for amateur use in which there is a sufficient bandwidth to accommodate the sidebands that will contain the information to be transmitted. The carrier wave on its own does not contain any useful information, beyond indicating an existence of a transmission. Instead, the information must be combined with the carrier by the process of modulation. Because ComReg, the ITU, and other regulators manage the spectrum allocation, offering a great choice of carrier frequencies, billions of simultaneous, non-interfering radio communications take place every day.

This chapter explains how the information, represented by analogue and digital signals are combined with a carrier frequency to become a radio wave. You will learn a few types of modulation and operating modes. To understand data transmissions, you also need to be aware of different ways of encoding data.

11.1 Carrier, Signal, Modulation, Bandwidth, and Sidebands

MODULATION is a way of impressing information onto a sinusoidal carrier wave.[164] The information being impressed is called the MODULATING SIGNAL. The result is called the MODULATED SIGNAL. The modulated signal is no longer sinusoidal. It can be viewed as a combination of the carrier frequency, unless the carrier has been suppressed, and a small or a large number of sidebands.[165]

The BANDWIDTH of the modulated signal spans from the lowest to the highest frequency within the sidebands, plus the frequency of the carrier, if the carrier is being transmitted.

All, or most, of the useful information is in the sidebands, and usually not at the carrier frequency.[166] SIDEBANDS contain the information being transmitted in the form of frequencies and amplitudes of the modulating signal. They also contain additional by-products of the modulation process.

164 Modulation can be applied to any *periodic* carrier signals, including non-sinusoidal periodic signals. However, amateur radio normally uses sinusoidal carrier waves. See 5.1 Sinusoidal Signals and 6.1 Non-Sinusoidal Signals.

165 Recall that any signal can be viewed in its frequency domain as a combination of its component frequencies. You can often see that on a waterfall plot on modern transceivers, where the frequencies are represented by the horizontal axis. See 6.2.1 for a discussion of *frequency* and *time domains*.

166 Carrier frequency contains some useful information in FM, even though the sidebands carry most of it. However, no useful information is in the carrier in AM.

The type of the modulating signal can be analogue or digital. There are many ways, known as types of modulation, to modulate a carrier wave using those signals. Each has its advantages and disadvantages, and different uses.

11.2 Type of Modulation vs. Operating Mode

To transmit anything using radio, including voice or data, that information has to be somehow impressed upon the radio waves at and near a chosen CARRIER WAVE FREQUENCY. The frequency of the carrier is selected using the radio's main tuning knob, generally referred to as the VFO.[167]

The OPERATING MODE determines what type of information is being transmitted and how it is being converted (encoded) into a low-frequency modulating signal, such as an AF voice signal.[168] The TYPE OF MODULATION determines how this low-frequency modulating signal is then combined with the RF carrier wave, and what additional processing, such as filtering, must be applied to the resulting modulated signal before it can be transmitted from an antenna. Another common term used to describe the type of modulation is MODULATION SCHEME.

For example, 3650 kHz is the carrier frequency of the IRTS Sunday noon news service. As this is a spoken news service, its operating mode is PHONE. There are other common operating modes: CW, which is a digital mode used for Morse code transmissions, other digital operating modes for data, and video.

To be able to transmit the voice of the newsreader, the audio coming from the microphone needs to be converted into a radio wave. The choice of the type of modulation determines how the microphone's AF modulating signal is combined with an RF carrier wave, whose carrier frequency has already been selected. A common type of modulation on the HF bands, and the one used by that news service, is Single Sideband (SSB). However, AM could have also been used for phone purposes, while on VHF and higher bands FM is popular for the phone operating mode. All those acronyms will be explained when each modulation scheme is discussed in this chapter.

Those modulation schemes can be also used with operating modes other than phone, i.e., CW, digital, and video. Video and digital modes can use many different ways to encode the information before it is modulated. Digital information is commonly encoded, i.e., converted into a sequence of bits (zeroes and ones) or more complex symbols. When discussing digital operating modes, it is important to know not only which type of modulation is used, but also their encoding mechanism. For example, even though RTTY and Franke & Taylor 8 (FT8) digital modes both use Frequency Shift Keying (FSK) which is a type of FM modulation, the textual information is encoded very differently in those two operating modes. Decoders for RTTY will not work for FT8.

167 The tuning knob is named after the Variable Frequency Oscillator (VFO), a transmitter and receiver component which generates a pure sine wave at the selected frequency. See 8.6 Oscillators.

168 Another name for the modulating signal is *baseband*.

ITU EMISSION DESIGNATORS, such as J3E, are closely related to the type of modulation and the operating mode. They are summarised in section 20.6 Emission Designators. Each ITU designator describes three things: the type of modulation, type of the modulating signal, and the type of information being transmitted. The example J3E emission designator describes single sideband amplitude modulation with suppressed carrier (J), one channel analogue signal (3), containing telephony, i.e., voice audio information (E). J3E is the ITU emission designator of the SSB phone operating mode.

The ITU designators do not describe in detail the encoding schemes of the digital modes. They focus more on the type of modulation and the general type of information being transmitted rather than on the exact type of data encoding.

The rest of this chapter explains the most common modes and modulation schemes which you need to study. They are summarised in Table 11-A.

Table 11-A: Common operating modes and modulation schemes

Operating mode	Common modulation schemes
CW	CW ASK (type of AM)
Digital	RTTY FSK (type of FM) FT8 FSK (type of FM) PSK (type of Phase Modulation)
Phone	AM SSB (type of AM) FM

11.3 Analogue vs Digital: Type of Information Being Transmitted

The type of information being transmitted influences the selection of the appropriate operating mode and the modulation scheme. In general, information can be analogue or digital. Digital information needs to be converted to an analogue representation before it can be processed by traditional analogue modulators. Modern transceivers, on the other hand, use digital data and DSP to perform all modulation duties without the need for an interim conversion to an analogue representation, see section 6.2 Digital Signal Processing.

11.3.1 Modulation of Analogue Information

An example of ANALOGUE information is the audio frequency (AF) signal representing voice from a microphone. This signal is electrically represented by AF AC. Video and images can be also represented as analogue information.

The most common types of analogue modulation are AM, amplitude modulation with dual sidebands, and its close variant SSB, single sideband with suppressed

carrier, and FM, frequency modulation. Phase modulation is another type of modulation, but it is rarely used for *analogue* information in amateur radio.[169]

11.3.2 Modulation of Digital Information: Bits and Symbols

An example of DIGITAL information is a text of a news article to be transmitted using radiotelegraphy. It can be encoded (converted) to a sequence of Morse characters: short DIT, longer DAH, and both short and longer PAUSES. When transmitted as CW, those Morse characters are represented by a sequence of on and off periods during which the carrier wave is or is not being transmitted. Each of those periods can be thought of as a BIT of information, equal in its duration to the Morse dit character,[170] representing one of two possible states: either the on or the off state of the carrier for that short duration of time. Different letters are represented by a different number of dits and dahs, and so a different number of bits, in Morse code.

Alternatively, each letter of the same text could be converted into a sequence of exactly five bits, as used by RTTY. In this method, each bit is transmitted as one of two possible tones (frequencies), known as the mark and the space frequency. This is the principle of Frequency Shift Keying (FSK) Yet another way to encode the text would be to convert it into a sequence of other more complex SYMBOLS, as used by FT8 (FSK), or some Phase Shift Keying (PSK) applications and other modulation schemes.

The main difference between bits and symbols is that a bit can only represent two possible values, such as the on-off state of CW. On the other hand, there are more than two possible states one symbol can represent. It can represent one of many values: in 4-PSK (QPSK) there are four symbols, and in FT8 there are eight symbols represented by eight different tones.

The most common types of digital modulation are CW (Continuous Wave) which is a form of Amplitude Shift Keying (ASK), FSK, and PSK . Note how the names of those digital types of modulation are very similar to their analogue equivalents., except that instead of being called a modulation, they are called SHIFT KEYING.

Keying, in this context, means a way of encoding text and other digital data into a sequence of precise changes to the otherwise steady amplitude, frequency, or phase of the carrier wave. The term keying comes from CW, where the steady carrier wave is keyed on or off to transmit Morse characters. The word shift, as in FSK, represents the shift (change, deviation) of the transmitted carrier between two different frequencies.

169 Phase modulation and frequency modulation are closely related to each other. They are both forms of *angle modulation*, not to be confused with AM, amplitude modulation.

170 The duration of a bit in CW is that of a Morse dit without a following space. *Dit* is the shortest duration of the *on* transmission period. It is always followed by a pause, represented by the *off* period, lasting the same amount of time. That means a dit is an on followed by an off, both the same duration. A *dah* is defined as an *on* period lasting the duration of three dits, followed by a short pause lasting in duration the same as a dit. In other words, a dah consists of four bits: three ons followed by one off. All letters and numbers are built from those dits and dahs, with an additional space, equal to three off periods, between letters, and an even longer space, of seven offs, between words.

11.3.2.1 *Bit Rate, Symbol Rate (Baud Rate), and Words-per-Minute (WPM)*

Digital information can be sent at different speeds. Bit rate and symbol rate describe how many bits or symbols are sent in one second. WORDS-PER-MINUTE (WPM) is a more natural description of how many words of normal text can be sent using a given mode in one minute.

It is important to know the bit rate, the symbol rate, or WPM of a digital transmission because have an impact on the bandwidth necessary for its successful reception.

CW is a digital mode in which the time to send each character differs because different letters of the alphabet use a different amount of dits and dahs. It is not common to describe CW speed in terms of its bit rate or symbol rate. Instead, speed is expressed in WPM using a word of an average length.[171] A common range of conversational CW speeds in amateur use is 10–25 WPM, but both much higher and lower speeds have their uses.

BIT RATE, or bitrate, determines how many bits of information are sent in one second. Since a bit can represent only two values, like a 0 or a 1, or an *off* and an *on,* information has to be encoded into bits before transmission. It takes several bits to encode each character.[172] Bit rate is measured in BITS PER SECOND (bit/s).[173]

SYMBOL RATE, also known as BAUD RATE, and which is expressed using a unit called a BAUD, determines how many symbols are sent per second. For example, FT8, which uses symbols representing 8 different tones, has the speed of just over 6 baud, i.e., it transmits slightly more than 6 symbols per second. Bit rate and symbol (baud) rate are not equivalent.[174]

11.4 Amplitude and Frequency Modulation

Almost all types of modulation used in amateur radio, both for analogue and digital information, are based either on Amplitude Modulation (AM) or Frequency Modulation (FM). The fundamental form of AM and FM is explained in this section. Later sections explain how AM and FM have been adapted to suit different types of modulating signals, and different available bandwidths.

171 By convention, the word PARIS is used for this purpose. That word consists of exactly 50 bits, i.e., on and off periods of equal duration, including the pauses between characters, and the 7-dit pause at the end of each word. It is possible to covert the WPM of CW to its bit rate. CW bitrate = WPM/1.2. 12 WPM CW has a bit rate of 10 bit/s.

172 You may be familiar with the ASCII encoding popularised by personal computers in the early '80s. It uses 8 bits to encode English letters, numbers, and a few other European language letters. It was surpassed by Unicode, which uses 16 or more bits, and which supports all languages, special characters, and emojis. In amateur radio you will come across *Baudot Code* which uses 5 bits to encode English letters and numbers. It was invented in 1870 by Émile Baudot, a French telegraph engineer and inventor. Its variant is used by RTTY. The term *Baud rate* is named after the inventor.

173 bit/s is sometimes referred to as bps. Internet DSL (Digital Subscriber Line) broadband speeds usually use Mbit/s, or Mbps (megabits per second) and fibre broadband uses Gbit/s or Gbps.

174 Baud rate is equal to bitrate only in those modulation schemes which use bits as symbols, for example in PSK31. When there are more than two symbols, such as in FT8, which uses eight symbols for its eight tones, the symbol rate, i.e., its baud rate, is quite different from its bit rate. FT8 bitrate is 18.75 bits/s, while its symbol rate is 6.25 symbols/s, that is, 6.25 baud.

Study the plots shown in this section to understand the differences between AM and FM. To make the concepts easier to see on a plot, the carrier frequency has been chosen to be an artificially low 30 Hz, while the modulating signal is a single sine wave with the frequency of 6 Hz. To keep things simple, they both have the same amplitudes. Realistically, the frequency of both would be much higher. A real-world carrier frequency would be thousands or millions of hertz – many kHz or MHz. A real-world amateur radio modulating signal, however, could have a low frequency of just a few Hz, as used by some digital modes, or as high as 3 kHz when carrying phone voice.[175]

Figure 11-i (next page) shows a carrier wave whose frequency is 30 Hz. If you count its full oscillations, for example the troughs or the peaks, you will see there are 30 of them because the horizontal axis shows exactly 1 second of time. The modulating signal is just a simple 6 Hz sine wave. It is shown in Figure 11-ii.

11.4.1 Amplitude Modulation

In AM, the amplitude of the modulating signal is used to vary the amplitude of the carrier wave. The resulting modulated signal's amplitude closely resembles the amplitude of the modulating signal. Figure 11-iii on page 147 shows the resulting, amplitude modulated signal as the red trace. The plot shows how the amplitude of that modulated signal (red) changes to match the changing amplitude of the 6 Hz information (blue) being impressed upon the 30 Hz carrier wave (green).[176] Notice the symmetry of the upper and the lower edges of the modulated signal, which both follow the shape of the blue modulating signal's waveform and thus carry its information.

175 Non-amateur radio applications can use modulating signals with a much higher frequency and bandwidth. For example, the frequency of the modulating signal representing the data sent using Wi-Fi can have MHz or even GHz frequencies to transfer information at hundreds or thousands of Gbit/s. This is possible even though WIFI carrier frequency is also in the GHz range, usually 2.4 or 5 GHz. Commercial FM radio would have as much as 75 kHz and a single TV transmission carries several MHz, or more, of modulating signals, both in its analogue and digital variants.

176 To make things easier to see on the plot, the modulating signal in Figure 11-iii and on all subsequent, similar plots has been moved upwards by a factor of 1, which is the amount of the carrier's amplitude.

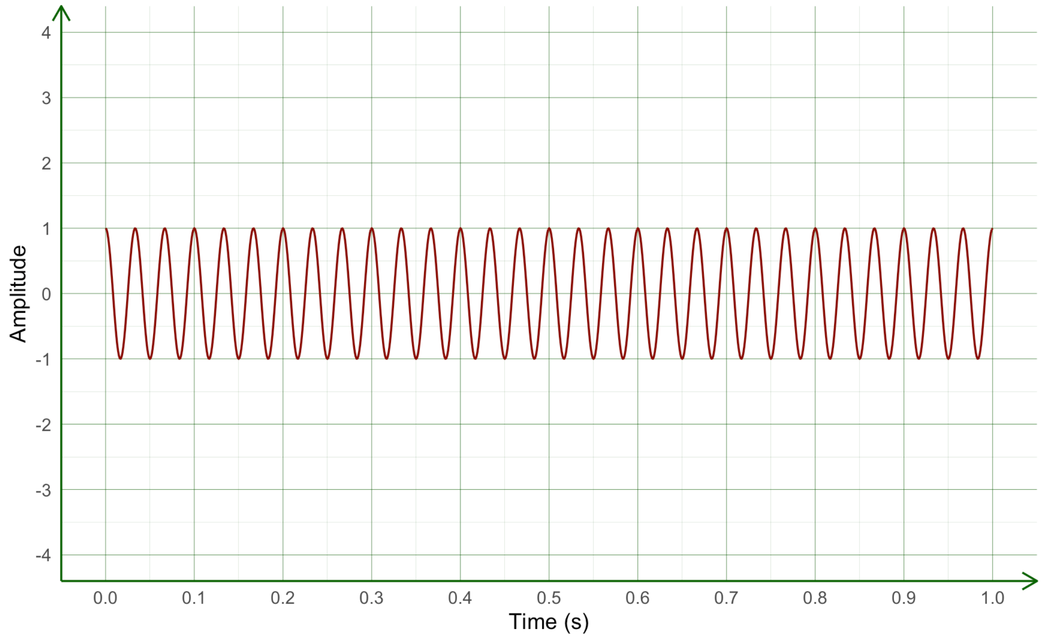


Figure 11-i: 30 Hz carrier wave. [EI6LA]

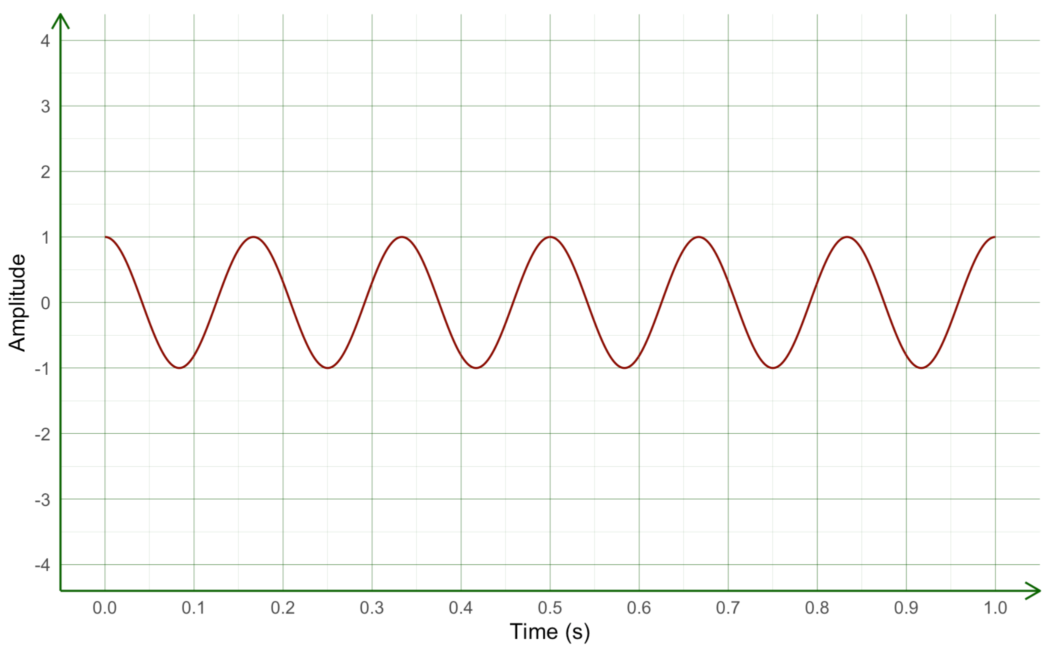


Figure 11-ii: 6 Hz modulating signal. [EI6LA]

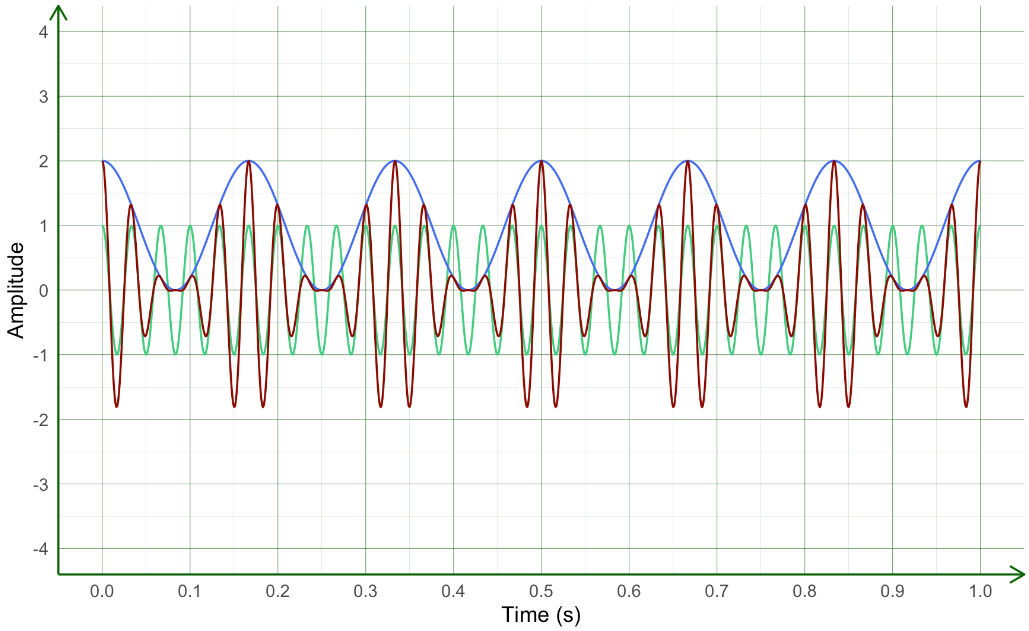


Figure 11-iii: AM of a 30 Hz carrier using a 6 Hz signal. Red trace shows the modulated signal. Compare with the unmodulated carrier (green) and the modulating signal (blue above red). [EI6LA]

Recall from section 6.2.1 that these plots show the signals in their time domain because the horizontal axis shows time. While a time domain plot makes it clear how the signal changes as the time passes, it does not make it easy to see the new frequencies that the modulated signal consists of. To see the full spectrum of the modulated signal, it needs to be plotted in its frequency domain, just like on a waterfall display of modern receivers.

Figure 11-iv on the next page shows the frequencies on the horizontal axis. It is a frequency domain plot, i.e., a plot that shows the frequency spectrum of the signal. This plot is very simple because the modulating signal contains only one frequency. There are plots of more complex AM transmissions later on in this chapter.

This is the simplest form of AM, which is also known as double sideband amplitude modulation (DSB) with a full carrier.

Notice that there are three frequencies in the modulated signal, not just the two that were combined by the process of modulation.[177]

1. original carrier frequency of 30 Hz
2. LOWER SIDEBAND (LSB) at 24 Hz, which is 30 Hz – 6 Hz
3. UPPER SIDEBAND (USB) at 36 Hz, which is 30 Hz + 6 Hz

177 Actually, there would be four frequencies in the modulated signal. The three described above, plus the original frequency of the modulating signal. However, that frequency would never be transmitted by the radio because it would be much lower than the radio frequencies. If it were transmitted, it would most likely appear in an unauthorised section of the band plan. That frequency would be high-pass filtered, even though its amplitude may already be quite low because of the way AM works.

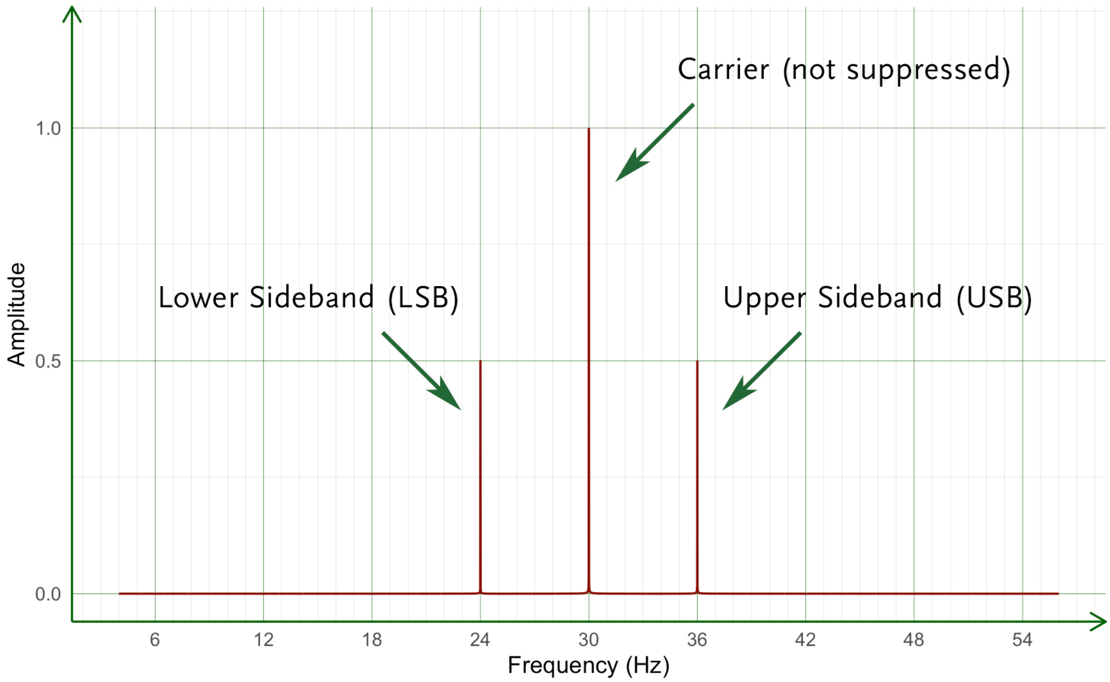


Figure 11-iv: Frequency domain of amplitude modulation of a 30 Hz carrier using a 6 Hz signal. Notice the 30 Hz carrier and the two sidebands, at 24 and 36 Hz. [EI6LA]

Understanding that the process of modulation always creates sidebands is fundamental to understanding how modulated radio waves carry information. In the case of amplitude modulation, for every frequency of the modulating signal, two new frequencies are created: one at the sum, and one at the difference of the carrier frequency and of each frequency contained in the modulating signal.

11.4.1.1 *AM Bandwidth*

An important implication of this modulation process is that each of the two sidebands will be as wide as the span from the lowest to the highest frequency contained in the modulating signal. For example, if the information being impressed on the carrier wave was 3 kHz wide, each sideband would be 3 kHz. The overall bandwidth of that modulated signal would be 6 kHz. The most basic form of AM requires a bandwidth that is twice as wide as the bandwidth of the modulating signal. This may be a too much for some applications.

Another disadvantage of this simplest form of AM is that the carrier frequency that is still contained in the modulated signal has a significant amplitude, equal to that of the unmodulated carrier wave, yet it contains no useful information. This wastes a lot of power because only the sidebands contain useful information. As explained later, it is possible to improve AM to be more efficient and less bandwidth hungry.

11.4.1.2 *AM Modulation Index*

The AM MODULATION INDEX denoted by letter m is usually expressed as a percentage. It indicates how much of the amplitude of the carrier is varied as a result of modulation. It is also known as modulation level or modulation depth.

For example, when $m = 0.5$, i.e., when it is 50%, the carrier amplitude varies by 50% above and below its unmodulated level. See how the red trace, which shows the modulated signal in Figure 11-v, never reaches zero. Instead, it always varies between 0.5 and 1.5 amplitudes. Since the carrier's amplitude is 1, the maximum change of the modulated amplitude 0.5 is 50% of the unmodulated carrier amplitude.

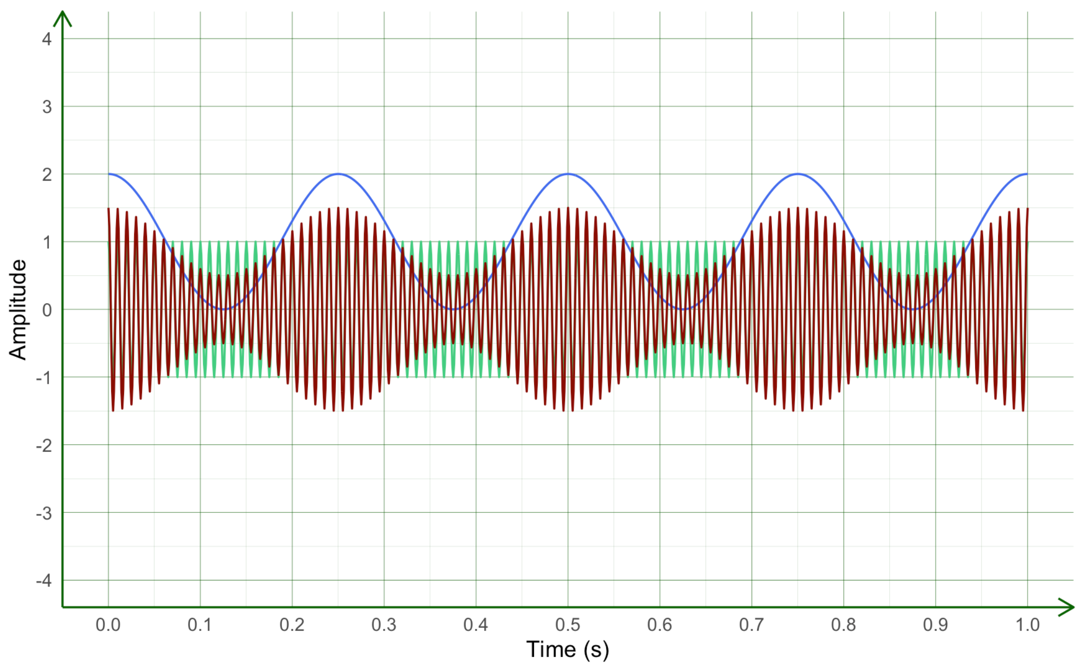


Figure 11-v: 50% AM modulation index (red trace). 100 Hz carrier (green) and 4 Hz signal (blue, shifted up by 1 for ease of comparison). Notice the amplitude of the red trace (–1.5 to 1.5) varies by 0.5 of the amplitude of the grey trace (–1 to 1). [EI6LA]

With FULL MODULATION, the modulation index is 100%, i.e., $m = 1$. It means the carrier wave's amplitude at times reaches the zero level, and at times it doubles its original amplitude. This is a desirable situation because it provides for the highest signal-to-noise ratio. The red trace in Figure 11-vi (next page) spans from 0 to 2, and 0 to -2.

It is important not to exceed this level. When modulation index exceeds 100% (m is greater than 1) sound and information will be clipped (distorted) and may become unreadable, see Figure 11-vii. This is OVERMODULATION should be avoided.

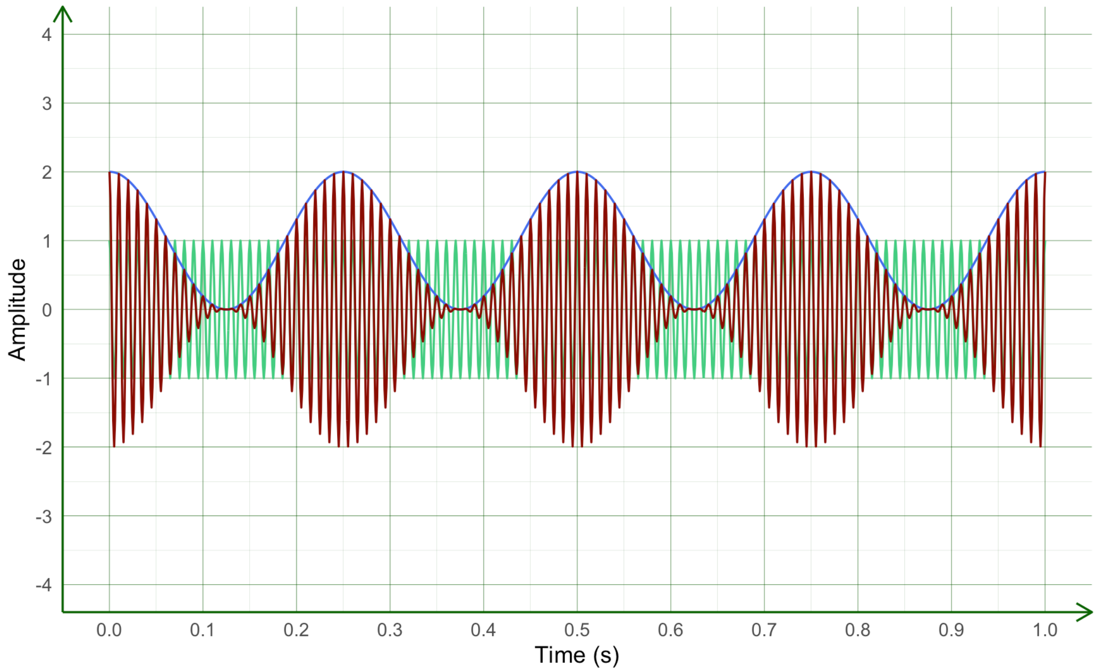


Figure 11-vi: Full modulation. 100% AM modulation Index (red). 100 Hz carrier (green) and 4 Hz signal (blue, shifted up by 1 for ease of comparison). Amplitude of the red trace (–2 to 2) varies by 1 amplitude of the grey trace (-1 to 1). [EI6LA]

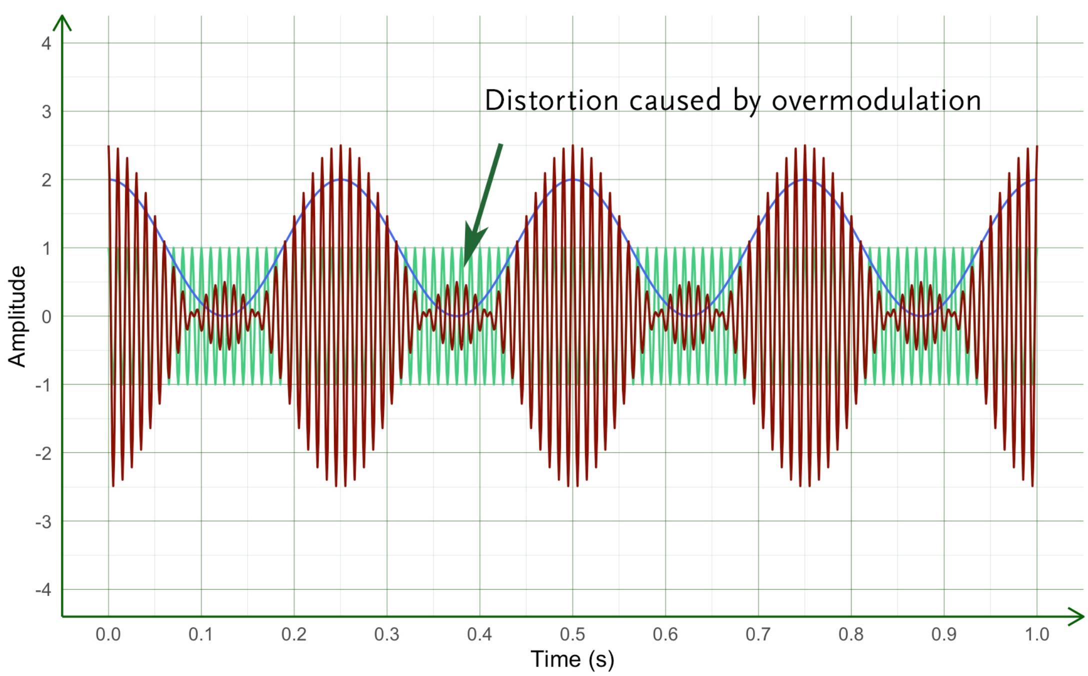


Figure 11-vii: Overmodulation. 150% AM modulation index (red). 100 Hz carrier (green) and 4 Hz signal (blue, shifted up by 1 for ease of comparison). [EI6LA]

The formula for m is simply the ratio of the maximum change of the modulated amplitude to the unmodulated amplitude:

$$\text{AM Modulation Index} = \frac{\text{max change of modulated amplitude}}{\text{carrier amplitude}}$$

Using the example of overmodulation in Figure 11-vii, the amplitude of the modulated signal (red trace) is -2.5 to 2.5. The amplitude of the carrier (grey trace) is -1 to 1. That means the modulated amplitude varies by 1.5 of the amplitude of the carrier. The AM modulation index $m = 1.5/1 = 1.5$ in this case, or 150%. There are other types of overmodulation that can affect AM.[178]

11.4.1.3 *AM and Noise*

AM is the oldest type of modulation that is still used in radio, even if not as widely as in the twentieth century era of major AM broadcast stations. It requires very simple hardware. However, in addition to its high bandwidth requirements, it has other disadvantages, including its susceptibility to noise. Atmospheric noise (QRN) and fading (QSB)[179] readily affect the amplitude of all signals, and the effect on AM signal is significant, causing it to fade, and become as noisy as the conditions. Using full, 100% modulation ($m = 1$) helps in those situations to some extent.

11.4.2 Frequency Modulation

In FM the amplitude of the modulating signal is used to vary the frequency, rather than the amplitude, of the carrier wave. The resulting modulated signal amplitude does not change. Time domain plot in Figure 11-viii shows the frequency modulated signal as the red trace. You can see how the frequency of the modulated signal *deviates* from the original frequency of the carrier. Where the modulating signal amplitude (blue trace) is high (loud) the modulated frequency gets higher – the gaps between red peaks become narrower. Where the modulating amplitude is low (quiet) the modulated signal's frequency is lower – the gaps widen. Only in places where the modulating signal has a zero amplitude (silence) the frequency of the resulting wave matches the carrier.

The frequency domain plot of FM signal looks different to AM, see Figure 11-ix. Unlike in AM, FM generates many sidebands of different amplitudes, each separated from the carrier frequency by the frequency of the modulating signal. In our example, that means there is a sideband at every 6 Hz below and above 30 Hz. Technically, there is an infinite number of FM sidebands. However, only a handful of them matter. Only a few are strong, the remaining ones are very weak. The amplitude and the number of the important sidebands is controlled by the FM modulation index.

178 The example shows simple overmodulation using an ideal mixer. Realistically, and when using amplifiers, other types can occur, including zero-output amplitude, or flat-topping, which truncates the peaks of the modulated signal's amplitude, leading to splatter and other distortions.

179 Abbreviations, including QRN and QSB, are explained in Chapter 26.

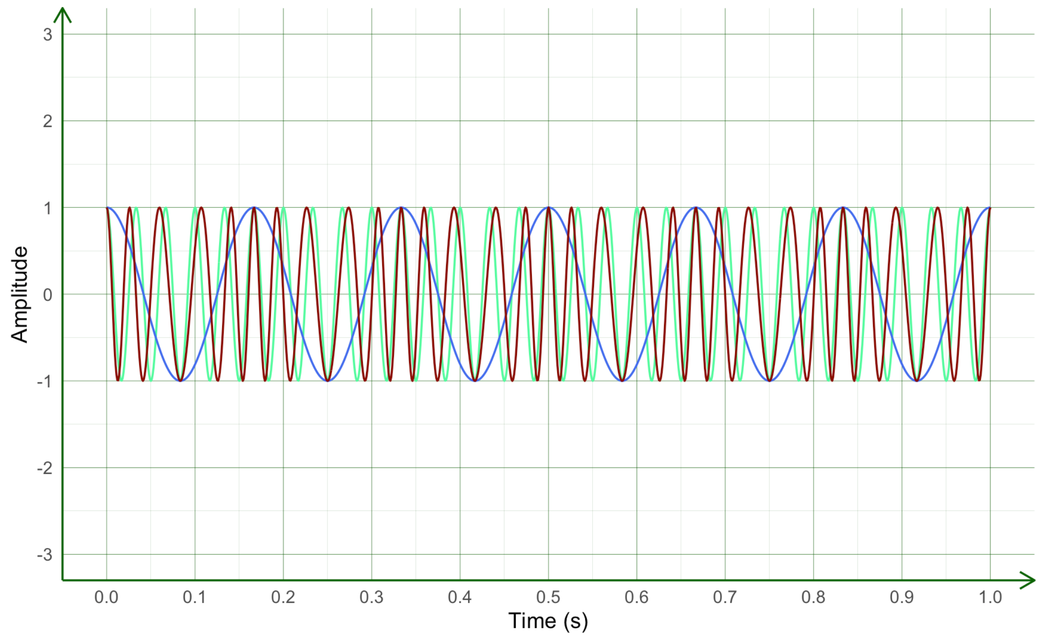


Figure 11-viii: Frequency modulation (FM) of a 30 Hz carrier using a 6 Hz signal, time domain. Modulation index 1.7. Red modulated signal. Green carrier. Blue modulating signal. [EI6LA]

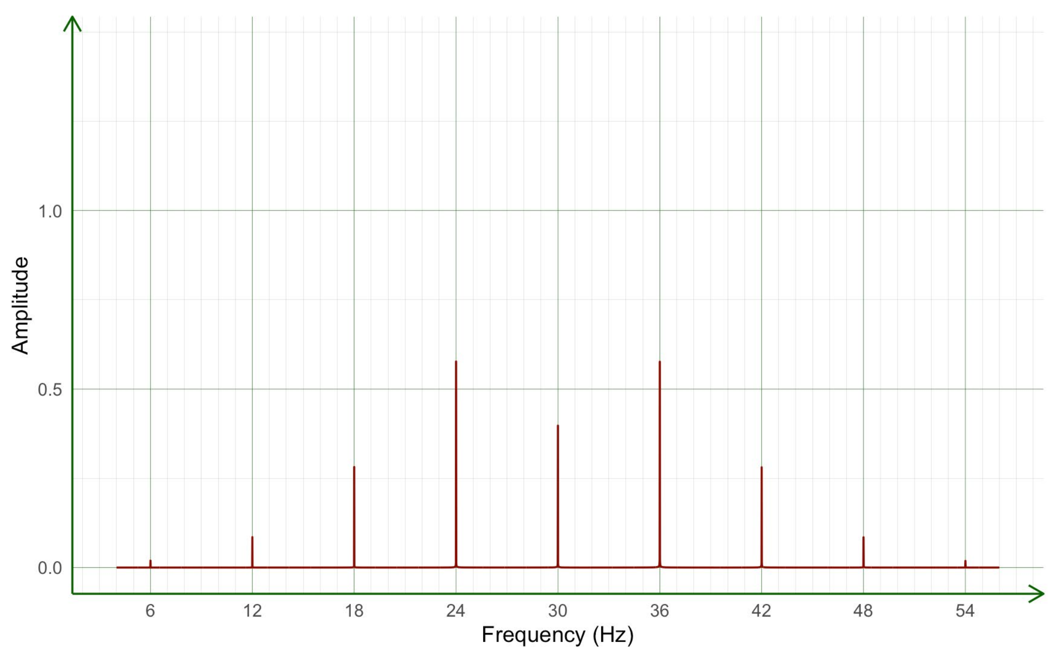


Figure 11-ix: Frequency domain of frequency modulation of a 30 Hz carrier using a 6 Hz signal and modulation index 1.7. Notice the 30 Hz carrier and many sidebands, at intervals of 6 Hz. [EI6LA]

Just like in AM, useful information is contained in all the sidebands. Unlike in AM, the carrier frequency of FM also contains some useful information.[180]

11.4.2.1 *FM Modulation Index*

The FM MODULATION INDEX denoted by letter m is usually expressed as a percentage. It indicates how much of the amplitude of the carrier is varied as a result of modulation. It is like its AM counterpart, except that it is concerned with the *frequency deviation* (change) rather than the change of the amplitude:

$$\text{FM Modulation Index} = \frac{\text{Peak Deviation}}{\text{Max Modulating Frequency}}$$

The PEAK DEVIATION describes how much the frequency of the modulated signal can deviate from the frequency of the carrier. Recall that in FM the frequency of the modulated signal deviates in proportion to the amplitude of the modulating signal.

For a given maximum modulating frequency, the value of peak deviation is normally chosen to make a good use of the bandwidth. A low value conserves the bandwidth by generating fewer sidebands, but it also reduces the signal-to-noise ratio.[181] A high value increases the bandwidth by creating more sidebands and improves the signal-to-noise ratio.

Peak deviation of 2.5 is typically used in amateur radio FM on VHF, such as the 2 m, 4 m, and 6 m bands, while 5 is used on the higher UHF frequencies, such as the 70 cm band.

The MAX MODULATING FREQUENCY is the highest frequency in the modulating signal. Phone (voice) in amateur radio normally uses no more than 3 kHz of audio frequency information.

Typical FM Modulation Indexes used on VHF and UHF are:

$$\text{VHF FM Modulation Index} = \frac{2.5\text{ kHz}}{3\text{ kHz}} = 0.8$$

$$\text{UHF FM Modulation Index} = \frac{5\text{ kHz}}{3\text{ kHz}} = 1.7$$

Note the difference between the UHF modulation index of 1.7 shown in Figure 11-ix and the same signal modulated using the VHF modulation index of 0.8 in Figure 11-x. Compare also the time domain plots of those two examples of FM modulation, as shown in Figure 11-viii and Figure 11-xi. The gaps between the peaks of the

180 The carrier frequency in FM acts like one of the FM sidebands. It appears when no modulating signal is present when the audio is silent. It shifts towards a sideband when volume increases. The FM carrier's presence or absence carries information about silence.

181 Since frequency deviation is proportional to the amplitude of the modulating signal, such as the volume of the audio information, a smaller peak deviation means a smaller range of amplitude values that can be modulated. This either requires a reduction in the dynamic range to maintain the same signal-to-noise ratio (SNR), or a reduction of SNR whilst accommodating the same dynamic range.

modulated signal (red trace) are narrower with the lower 0.8 modulating index than the wider gaps when using the 1.7 modulation index.

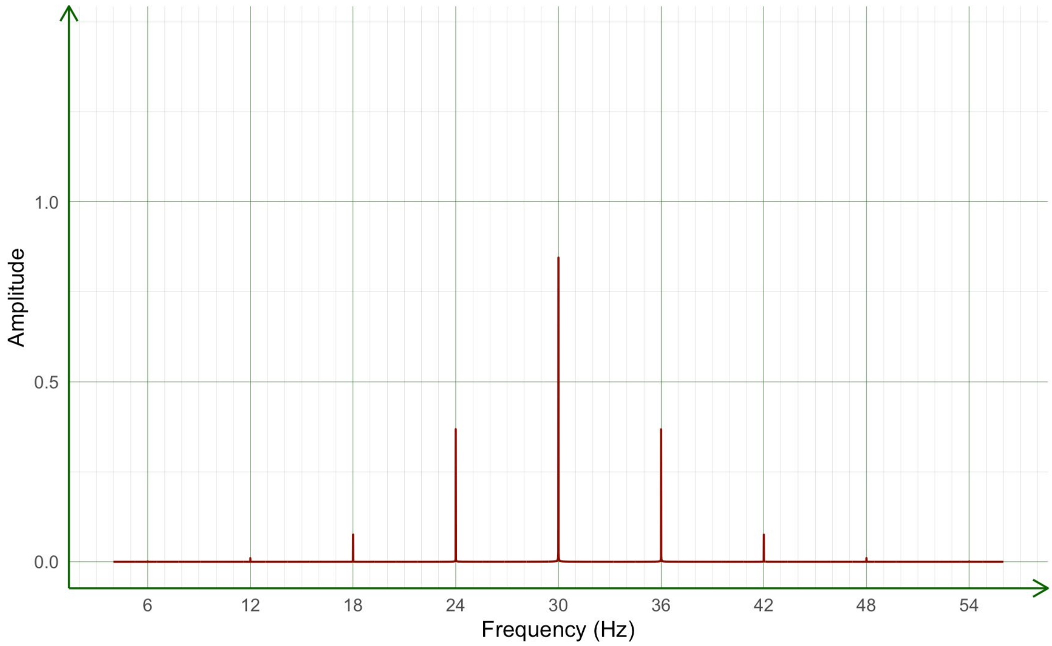


Figure 11-x: Frequency domain of FM. 30 Hz carrier, 6 Hz signal, modulation index 0.8. [EI6LA]

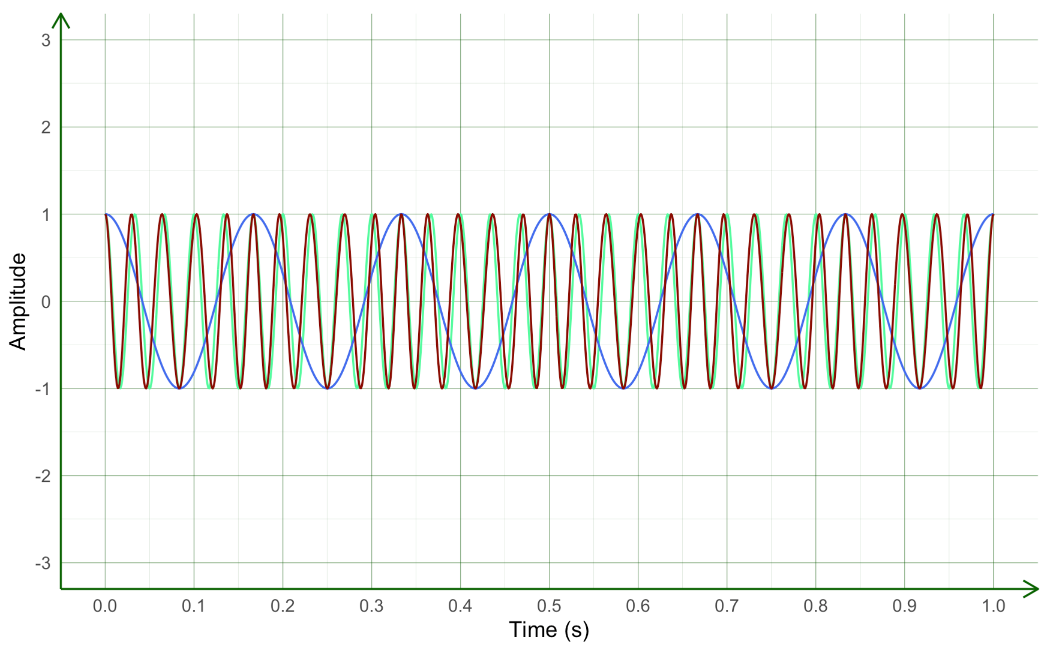


Figure 11-xi: FM. 30 Hz carrier, 6 Hz signal. Modulation index 0.8. See how the modulated frequency (red) barely deviates from the carrier frequency (green), less than with modulation index 1.7 shown in Figure 11-viii on page 152. [EI6LA]

11.4.2.2 *FM Bandwidth: Carson's Rule*

The bandwidth of an FM signal depends both on the FM modulation index, which determines the number of significant sidebands, and, as in AM, on the maximum frequency of the modulating signal. It is easy to estimate the necessary bandwidth using CARSON'S RULE.[182]

$$\text{FM Bandwidth} = 2\ (\text{Peak Deviation} + \text{Max Modulating Frequency})$$

Using this formula, the necessary bandwidth for FM phone (voice) on VHF and UHF would be:

$$\text{VHF FM Bandwidth} = 2 \times (2.5\ \text{kHz} + 3\ \text{kHz}) = 11\ \text{kHz}$$

$$\text{UHF FM Bandwidth} = 2 \times (5\ \text{kHz} + 3\ \text{kHz}) = 16\ \text{kHz}$$

Those two types of FM which use modulation indexes 0.8 and 1.7 are popular in amateur radio. They are known as NARROW-BAND FM (NBFM).[183]

To avoid interference, use of FM on VHF and UHF bands is CHANNELISED. Instead of selecting an arbitrary frequency, the transmitting station selects a predefined frequency channel. Channels have a predetermined width which is directly related to the above bandwidths. On VHF channels are spaced at 12.5 kHz intervals, and on 70 cm UHF band 25 kHz spacing is used.[184]

11.4.2.3 *FM and Noise*

Unlike AM, FM transmissions can be very clear even in the presence of both natural noise (QRN) and even some light fading (QSB). Generally, noise adds or subtracts from the amplitude. However, FM does not rely on the amplitude to carry information, unless the impact of noise is so great that the signal is completely lost. Unfortunately, unlike AM, FM usually requires more bandwidth, and more complex equipment.

182 Carson's bandwidth rule for sinusoidal signals, which is shown above, determines the bandwidth within which there is 98% of the transmitted power of an FM signal. Some regulations may require a more precise determination of the bandwidth where 99% of the transmitted power lies, in which case Carson's rule is not useful.

183 Wide-band FM uses modulation indexes greater than 2. It has better signal-to-noise ratios, but it also uses much more bandwidth because it requires more significant sidebands. For example, commercial FM stations use modulation index 5.

184 The only HF band that permits the use of FM is the 10 m band. According to ITU definitions, 10 m is not yet VHF, but HF. However, the segment of 10 m frequencies allocated to FM is so close to the 30 MHz start of the VHF bands that the same parameters apply to it. There are some inconsistencies. For example, while the bandwidth required for VHF FM is generally 11 kHz, the IARU HF band plan only allocates 10 kHz channels, which may lead to some interference. Fortunately, FM is rare on 10 m.

11.5 AM (A3E)

This phone (voice) AM mode has the ITU designator A3E, which stands for: amplitude modulation with double sideband (A), one channel containing analogue information (3), telephony (E). It is commonly just called AM in amateur radio use.

The type of modulation used by A3E has been discussed in detail in section 11.4.1 Amplitude Modulation. As explained there, the *bandwidth* of a well-formed A3E is twice that of the modulating signal frequency, which in amateur radio phone use usually means 6 kHz.

Figure 11-xii a commercial station transmitting talk (phone) using AM A3E mode. Note the two sidebands, each approximately 5 kHz wide, and the overall 10 kHz bandwidth. Notice also the high power used by the carrier frequency, shown as a high peak and a bright green line, even though no information is contained in the carrier. All the useful information is contained only in the sidebands. This is an inefficient method of communication, both in terms of the bandwidth and power.

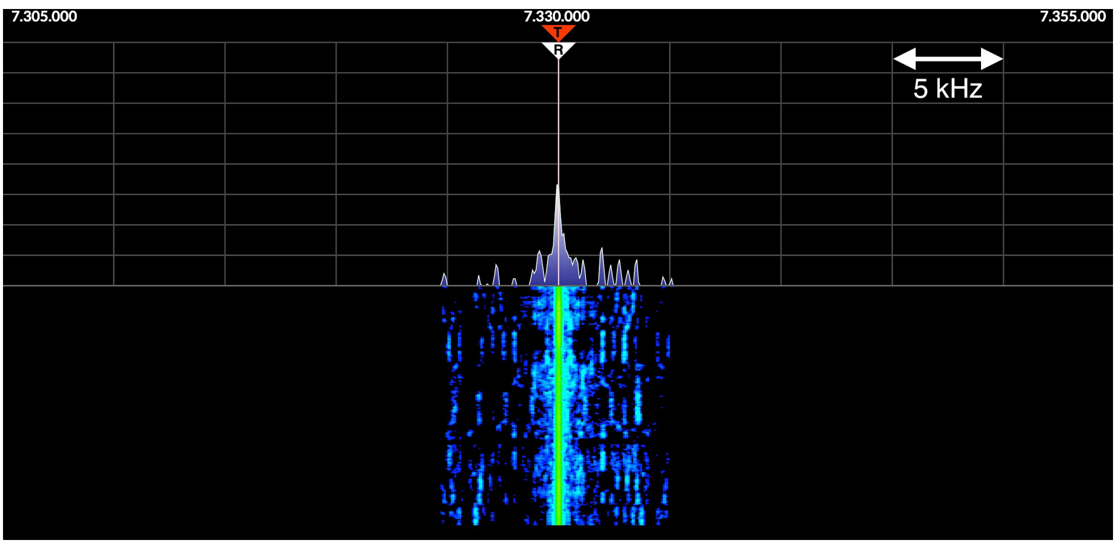


Figure 11-xii: AM phone (A3E) signal in frequency domain (upper half) and waterfall (bottom) plots. A commercial station using approximately 10 kHz of bandwidth, rather than the 6 kHz more typical in amateur use. [EI6LA]

A3E AM has been historically popular because it required only the simplest receivers and transmitters. The number of commercial A3E stations has dwindled, however, it still has specialised uses in aviation. Except for those dedicated to this mode, it is rarely used in amateur radio nowadays. On the MF and HF bands it has been replaced with SSB (J3E), and with FM (F3E) on the VHF and UHF bands.

11.6 SSB (J3E)

SINGLE SIDEBAND (SSB) is the commonly used short name for the most popular phone (voice) amateur radio mode on the MF and HF bands.[185] It is a form of AM. Its ITU designator is J3E, which stands for: amplitude modulation with single sideband suppressed carrier (J), one channel containing analogue information (3), telephony (E). SSB (J3E) is based on the AM modulation explained in detail in section 11.4.1, with two significant differences.

1 Only one of the two sidebands is transmitted: Lower Sideband (LSB) or Upper Sideband (USB).
2 The carrier is suppressed.

As a result, SSB requires less than half of the BANDWIDTH of AM (A3E) , about 2.6 kHz. Additionally, by not transmitting the carrier, all the transmitted power is in the sideband. Recall that the AM carrier does not contain any useful information. By not wasting power on the unnecessary carrier, SSB makes a very efficient use of power to transmit useful information.[186]

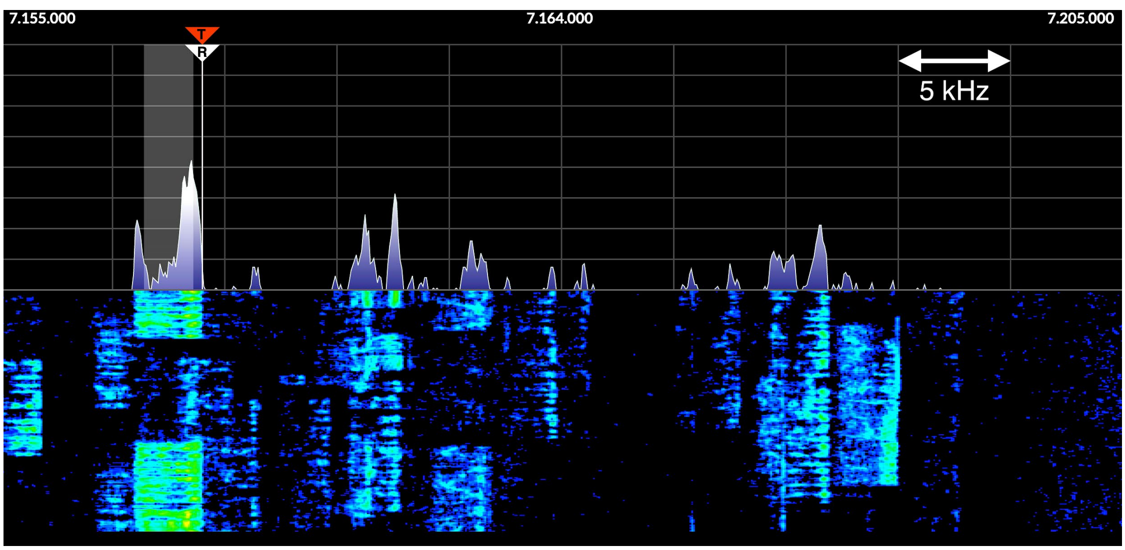


Figure 11-xiii: SSB (LSB) phone (J3E) signal in frequency domain (upper half) and waterfall (bottom) plots. The lower sideband containing phone communication lies below the carrier frequency (marked T-R) of 7.164 MHz. [EI6LA]

Figure 11-xiii shows several LSB transmissions. See how all the signal power lies below, i.e., to the left of the highlighted carrier frequency of 7.164 MHz: this is LSB.

185 It is common, even if technically incorrect, to say *HF bands* whilst meaning both MF and HF. See Table 7-A: ITU radio band names (subset: LF, MF, HF, VHF, UHF).
186 There are other benefits of not transmitting the carrier. It prevents receiver artefacts such as beats and heterodyne whistles.

In USB the signal power, which represents the audio information being transmitted, would be above, i.e., to the right of the carrier frequency. Notice also that there is almost no power at the carrier frequency because it has been supressed. Compare this to the high level of carrier power visible in Figure 11-xii.Most of the power in SSB appears close to but not at the carrier frequency. That power represents the lowest audible audio tones, such as the low tones of a bass voice, with the higher voice tones appearing further from the carrier, which is further below in LSB, and further above in USB.

Contrast the plot above with Figure 11-xiv, which shows USB transmissions. The upper sideband appears to the right of the selected supressed carrier frequency. Majority of the power now also appears to the right of the carrier, and it still represents the low tones of the audio, bass.

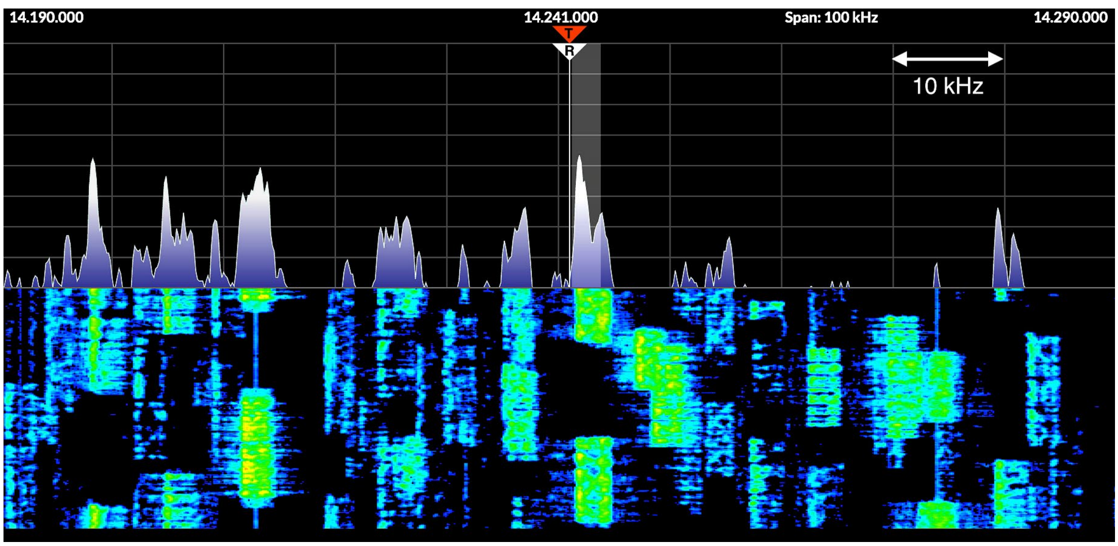


Figure 11-xiv: SSB (USB) phone (J3E) signal in frequency domain (upper half) and waterfall (bottom) plots. The upper sideband containing phone communication lies above the carrier frequency (marked T-R) of 14.241 MHz. [EI6LA]

11.7 FM (F3E)

This phone (voice) FM mode has the ITU designator F3E, which stands for: frequency modulation (F), one channel containing analogue information (3), telephony (E). It is commonly just called FM in amateur radio use. It is in widespread use for phone on VHF and UHF bands, and it is also widely used by commercial radio stations, and various public services.

The type of modulation used by F3E has been discussed in detail in section 11.4.2. As explained, the bandwidth of narrow-band FM (NBFM) used in amateur radio is approximately 11 kHz on VHF and 16 kHz on UHF. The bandwidth depends on the FM modulation index, explained in section 11.4.2.1.

Figure 11-xv shows a voice transmission on a VHF amateur radio band using FM (F3E). Notice the multiple, small, regularly spaced sidebands, characteristic to FM, which look quite different from AM (A3E), shown in Figure 11-xii on page 156.

You can also see that there is a fair amount of power in the carrier frequency of an FM signal. Even though all the FM sidebands contain useful information, the FM carrier also contains some information, and is a necessary part of FM (F3E). It cannot be removed like in SSB (J3E).

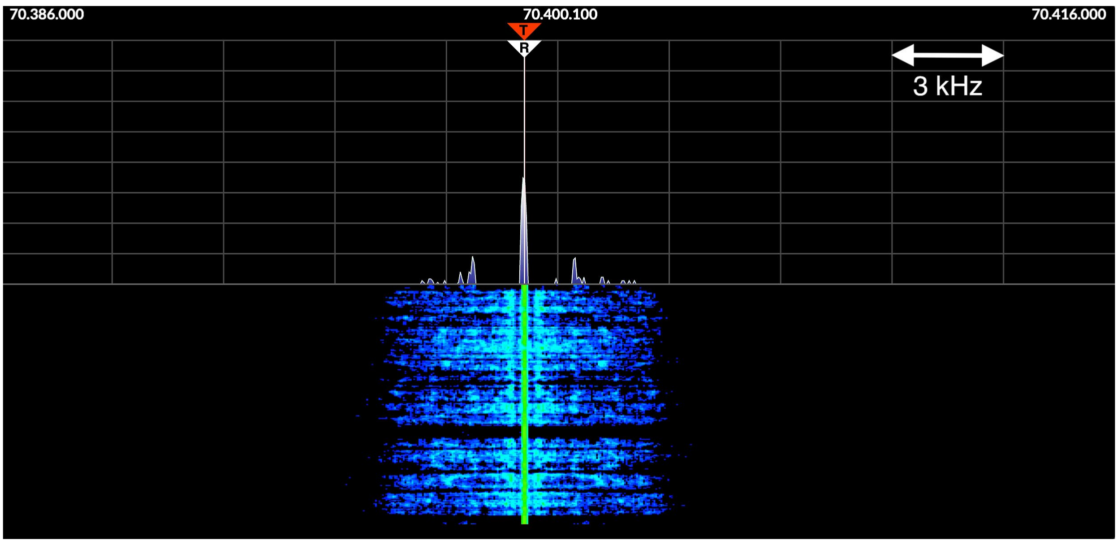


Figure 11-xv: FM phone (F3E) signal in frequency domain (upper) and waterfall (bottom). [EI6LA]

11.8 CW, ASK, OOK (A1A)

The CONTINUOUS WAVE (CW) is the oldest radio communication mode. It is a digital mode.[187] It has been designed for TELEGRAPHY: the transmission of text (telegrams) using Morse Code.

Originally, Morse Code was not used for wired telegraphy, before becoming the first method of radio communication.[188] While computers can be used to both generate and to aid in the reception of CW, it has been designed for manual sending using a manual telegraph (Morse) key, such as those shown in Figure 11-xvi on the next page, and for decoding by the ear of a trained operator. It is a very popular mode of communication in amateur radio because it is reliable even in poor conditions, and perhaps because it requires some enjoyable skill.

CW transmits Morse code characters by ON-OFF KEYING (OOK) of the carrier wave for the duration of each Morse symbol. See also section 11.3.2 Modulation of Digital Information: Bits and Symbols.

187 At its inception, CW was the only communication mode and there were no distinctions between digital and analogue. Nowadays it belongs in the digital category.

188 Because of land and undersea wires, the old name for telegrams was *cables*.

Figure 11-xvi: Morse keys. Left: straight key, an on-off switch causes the carrier to be transmitted when pressed. Right: paddle. Pushing the left fingertip generates a sequence of dits, right for dahs. Paddle requires an electronic keyer. Straight key can be connected to any CW transmitter. [EI6LA]

On-off keying is a form of AMPLITUDE SHIFT KEYING (ASK) because the amplitude of the carrier wave is shifted (changed) from zero (off) to its full amplitude (on). By using a manual Morse key, the operator can decide how long the on and off periods should be. ASK, as the name suggests, is a digital form of AM. This is represented in the ITU designator A1A: AM modulation (A), one-channel digital signal without subcarrier (1), telegraphy intended for aural, i.e., by the ear, reception (A) .

The name, continuous wave, may sound strange, considering the on-off nature of the keying. It is, however, quite accurate, because during the on periods the transmitter is sending a continuous sinusoidal signal at the carrier frequency.[189]

11.8.1 CW Modulating Signal (Keying Waveform)

The CW modulating signal, also known as the KEYING WAVEFORM, changes its amplitude from 0 (off) to 1 (on) to represent the Morse symbols, see Figure 11-xvii. Those changes can be caused by the operator using a manual key, who is closing and opening a contact to make the characters. This waveform is a type of a square wave (see section 6.1) and the transitions from 0 to 1 are much too rapid – being almost instantaneous. Modulating such a signal would cause excessive bandwidth use. The transmitter must smooth the resulting modulated signal, as shown further below.

11.8.2 CW Modulated Signal

No matter how CW modulation is done, whether by using a dedicated Morse transmitter, or by using AM to modulate the keying waveform, or by using DSP in modern transmitters, the resulting modulated signals are very similar. Figure 11-xviii shows the word PARIS modulated into a CW signal. The 30 Hz carrier is unrealistically low. It was chosen to make it easier to see the principles of CW modulation in a plot.

189 This is in contrast to the predecessor of CW, which used *pulses* of *damped waves* generated by *spark gap* transmitters. See footnote 144 on page 114.

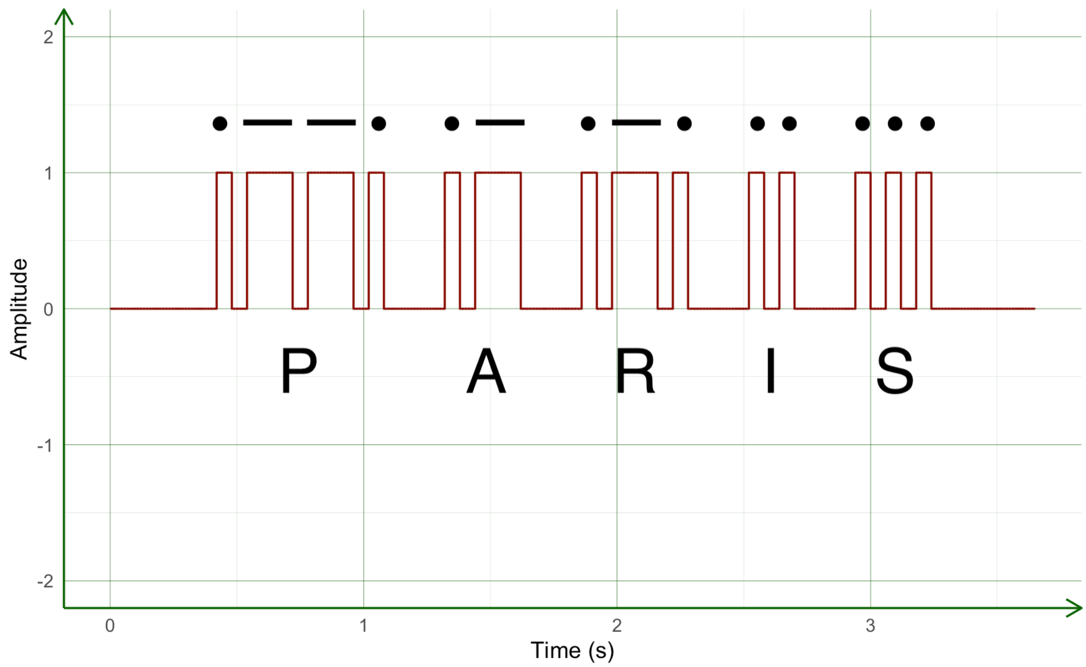


Figure 11-xvii: CW modulating signal (keying waveform) at 20 WPM. [EI6LA]

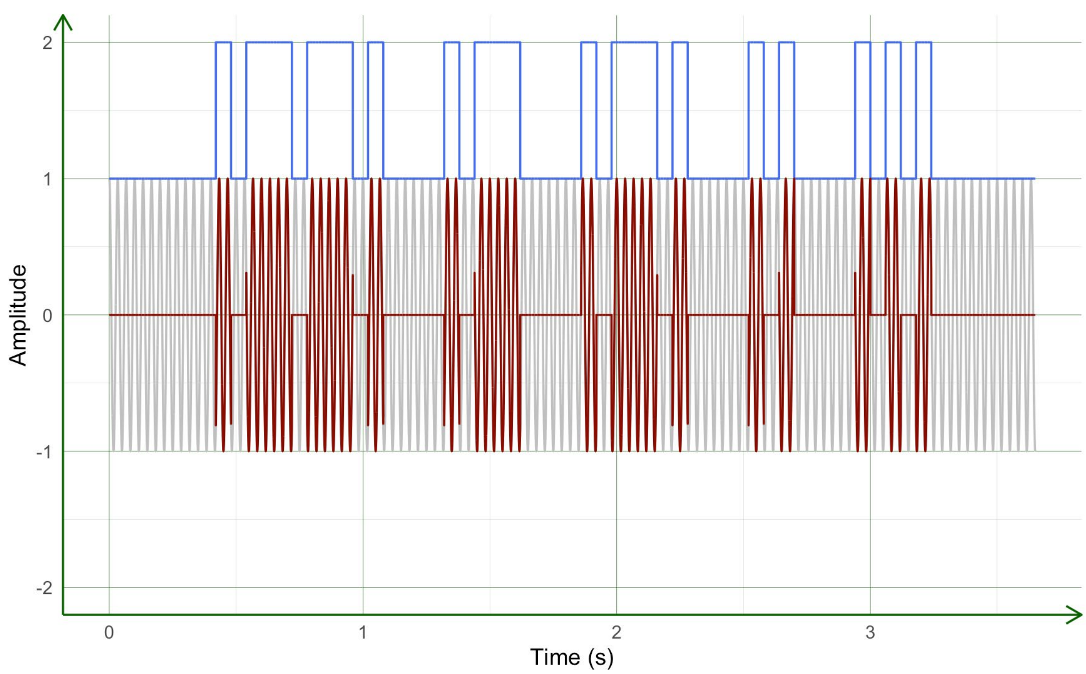


Figure 11-xviii: Modulated CW signal (red), 30 Hz carrier (grey). Modulating signal shown in blue, shifted up for readability. [EI6LA]

11.8.3 CW Bandwidth and Rise and Fall Times

The transitions between the off and on periods, i.e., between the zero and the full amplitude of the carrier wave, are not instantaneous. They take some time. This transition is known as the RISE TIME. The reverse, from on to off, is the FALL TIME.[190] They should be carefully chosen because they directly impact the bandwidth of both CW and any other ASK or similarly modulated signals.

Modern transmitters offer a choice of rise and fall times. A good choice is 6 ms. The bandwidth of CW using a 6 ms rise and fall times should not exceed 150 Hz, which makes CW an efficient, narrowband communication mode.

The IARU R1 band plans for the CW band segments limit the bandwidth of CW to 200 Hz. Much shorter rise times are possible, however, their bandwidths become EXCESSIVE, even larger than 1 kHz.[191] Any stations listening nearby will hear interference from the transmitting station as loud KEY CLICKS. See Figure 18-iv on page 289 for a frequency-domain plot showing such interference. To avoid those issues, rise times should be set at 4–6 ms or more. Alternatively, additional low-pass filters may need be employed. Any CW signal amplification should also ensure the absence of significant non-linearities, see section 10.7.4.

Much longer and gentler rise times, such as 20 ms, reduce bandwidth requirements of CW to as little as 40 Hz. However, their sound is smoother and only practical with relatively slower transmission speeds.[192] The bandwidth of a well-formed CW should be between 50–200 Hz.

Figure 11-xix shows two CW dits using a real-world carrier frequency of a few MHz. Notice the rising and falling edges of those CW signals. Although the left-hand waveform seems smooth, at 2 ms it is much too short. Both edges are also too sudden as can be seen from their sharp rather than rounded corners. This signal will cause key clicks and it will require far more bandwidth than necessary, over 1 kHz.

A better shape can be achieved by using low-pass key click filters, or by using a modern transceiver which generates CW using DSP and setting the rise and fall times to 4–6 ms, or longer. An example of a better signal is shown on the right-hand side. Such techniques for improving the waveform to reduce bandwidth requirements are known as PULSE SHAPING.

190 Another name for *fall time* is *decay time.*

191 If the rise time is much shorter, like 2 ms, the bandwidth increases to 400 Hz. With 0.5 ms, it uses 1.5 kHz of bandwidth. However, the rise time is not the only factor influencing CW bandwidth. The shape of the rising waveform is also important. A waveform that rises rapidly but as a sinusoid will require a lower bandwidth than a waveform with the same rise time but a straight-line, sharper shape. A poorly shaped 6 ms rising waveform may exceed 150 Hz bandwidth. Modern transceivers use DSP to generate well-shaped, bandwidth-efficient yet clearly audible 4–6 ms CW waveforms. Older equipment requires low-pass key click filters to create good quality, non-interfering CW.

192 Rise time of 6 ms allows real-world CW speeds of 40–50 WPM depending on band conditions. Rise time of 20 ms reduces the maximum real-world speed to about 10–15 WPM. This is why the speed of CW, in WPM, influences its bandwidth requirements indirectly, by setting an upper limit to the rise time, which, in turn, directly influences the bandwidth. See *ARRL Handbook,* section *Amplitude-Modulated On-Off Keying,* or search the Internet for *CW Bandwidth Rise Time WPM.*

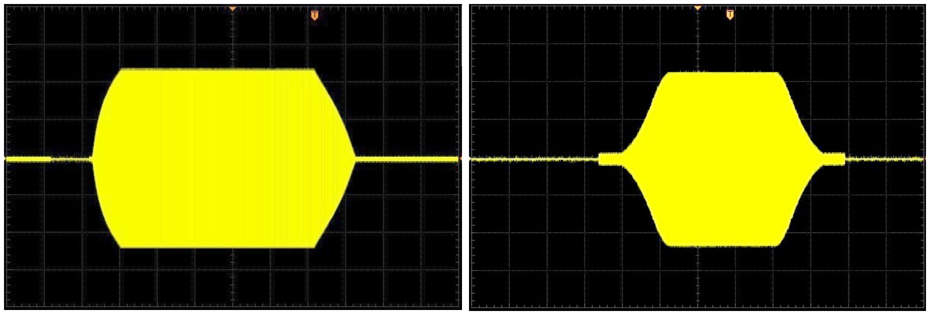


Figure 11-xix: CW keying waveforms of a single dit. Left: vertical divisions every 2 ms. Both rising and falling edges are too short, just under 2 ms, and too abrupt. Right: vertical divisions every 5 ms. Much smoother and longer duration of the edges, about 6 ms, with symmetrically rising and falling waveform shapes. [EI9ILB]

11.8.4 CW Sidebands

Like in all types of modulation, CW signal has sidebands within its bandwidth. Because CW is a form of AM, there are two sidebands. They contain useful information that represents the audible transitions between the off and on states.[193] You can see several CW signals and their relatively small sidebands in Figure 11-xx. All of the signals shown are approximately 50–150 Hz wide. Compare them with the excessively wide signal shown in Figure 18-iv on page 289.

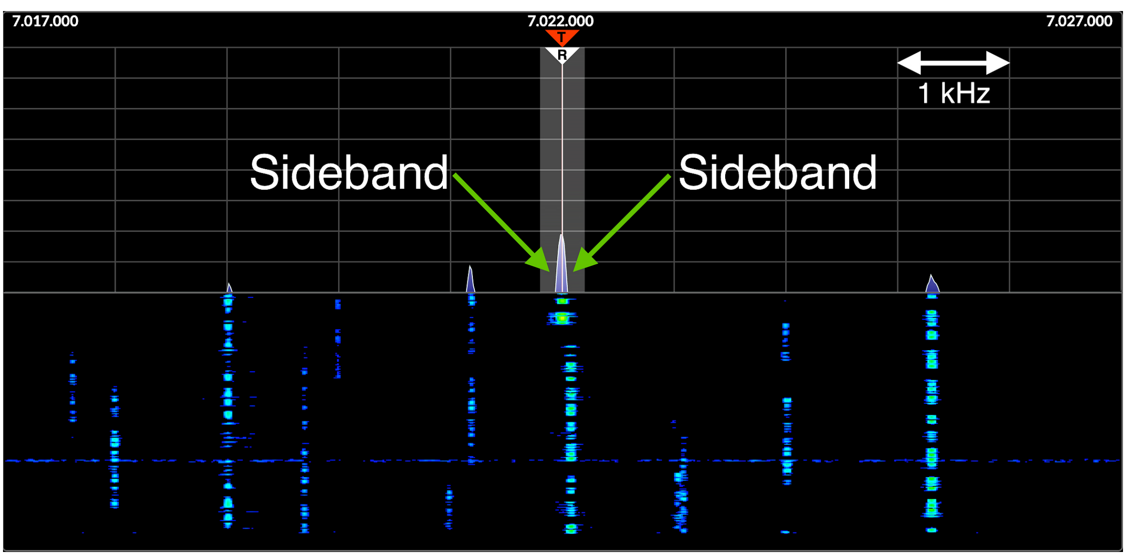


Figure 11-xx: CW signals in frequency-domain (upper half) and waterfall (bottom). Signal in the centre is approximately 150 Hz wide, with each of its sidebands approximately 75 Hz wide. [EI6LA]

193 Without the sidebands the CW signal would sound like a hum that is gently changing from loud to quieter and back. It would not be possible to hear the difference between dits and dahs.

11.9 RTTY, FSK (F1B)

The RADIOTELETYPE (RTTY) is the second oldest digital mode of radio communication.[194] It is still popular in amateur radio, especially during dedicated contests. Like Morse code, it was designed for telegraphy, the transmission of text.[195] It allows operators to chat with each other by typing on a keyboard. For those reasons, it is also referred to as a conversational digital mode of communication.[196] While RTTY used to rely on mechanical teleprinters, also known as teletypes (TTY), similar to electric typewriters, nowadays it is computerised.[197] Many modern transceivers include a decoder for RTTY, but it is more common to use specialised software on a computer connected to the transceiver.

The RTTY modulating signal is a sequence of symbols that represent the text to be sent.[198] While the encoding is different from Morse, the principle is the same: text is represented as a sequence of symbols, which are then used to modulate the carrier wave. RTTY uses Frequency Shift Keying (FSK) to modulate the carrier. It is a form of FM. The most popular form of RTTY shifts (changes, deviates) the frequency by 170 Hz, transmits 45 symbols per second (45 baud), and requires 300–500 Hz of bandwidth.[199] The ITU designator of RTTY is F1B: frequency modulation (F), single channel digital information without a subcarrier (1), telegraphy for automatic, i.e., machine or a computer reception (B) .[200]

Figure 11-xxi shows an example of an FSK modulated signal (red trace). To make the example more readable, the carrier (grey) has an unrealistically low frequency of 80 Hz, and the shift uses 60 Hz. The blue trace shows the modulating digital signal containing the text "CQ" encoded as RTTY symbols.

194 The oldest digital radio mode is CW. The US Navy Department successfully tested RTTY between an airplane and a ground radio station in 1922. See en.wikipedia.org/wiki/Radioteletype

195 RTTY, FT8, and other FSK digital modes can be also designated F1D, especially if used for data, telemetry, or telecommand. F1B is telegraphy: human readable text not requiring further processing.

196 Future IARU band plans distinguish between conversational digital modes, such as RTTY, PSK31, or Olivia, and *time-synced digital modes,* such as FT4 or FT8.

197 There are many programs for RTTY. Popular ones include fldigi, MMTTY, 2Tone, and Gritty.

198 RTTY uses ITA2 encoding scheme, sometimes referred to as the *Baudot Code,* from which it was derived in 1924. It uses symbols called *mark* and *space* to represent information. They are like bits. Each alphabet character uses 5 symbols. There are special codes to indicate if the subsequent character is text or a number, and control codes. One space symbol precedes each sequence, and 1.5 mark symbols follow it, to synchronise the stations. In total, each character is encoded as 7.5 symbols. Popular speed of RTTY is 45.45 baud, about 6 characters per second, or approx. 50 WPM.

199 In CW, the bits of information represent on and off states of the carrier, whose amplitude is changed from full to none. In RTTY the bits represent two tones. They are two frequencies that are 170 Hz apart. It is possible to listen to them using LSB to tune and troubleshoot RTTY communication.

200 RTTY can be generated in other ways than FSK. A popular is AFSK (audio FSK). Modem software modulates the data as an audio *subcarrier* signal that contains two tones separated by 170 Hz. It is then transmitted using SSB (LSB) like voice. If the entire system, the transceiver, computer, modem software, the audio devices, are all properly set-up, the modulated signal can be indistinguishable from FSK. The ITU designator of AFSK is not F1B but J2B: SSB (J), one channel containing digital information with the use of a modulating subcarrier (2), telegraphy for automatic reception (B).

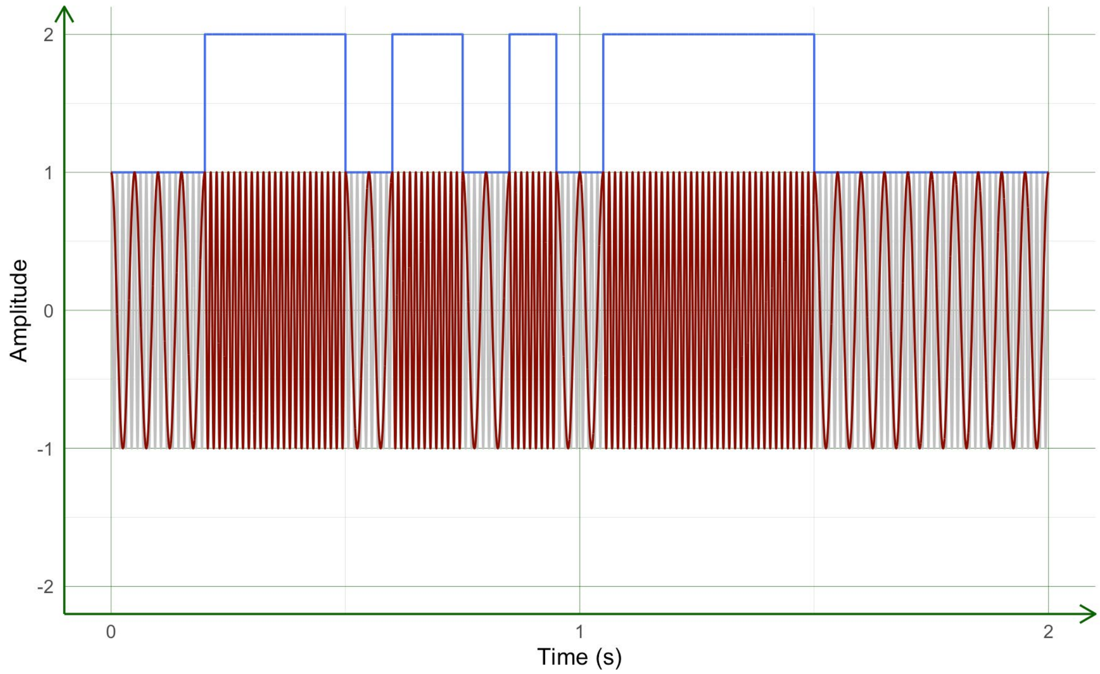


Figure 11-xxi: Modulated FSK signal (red). Modulating RTTY signal (blue, moved up for readability), 80 Hz carrier (grey). Shift 60 Hz. Lower-frequency sections representing space symbols in the modulated signal are 20 Hz, while the mark symbols are 80 Hz. [EI6LA]

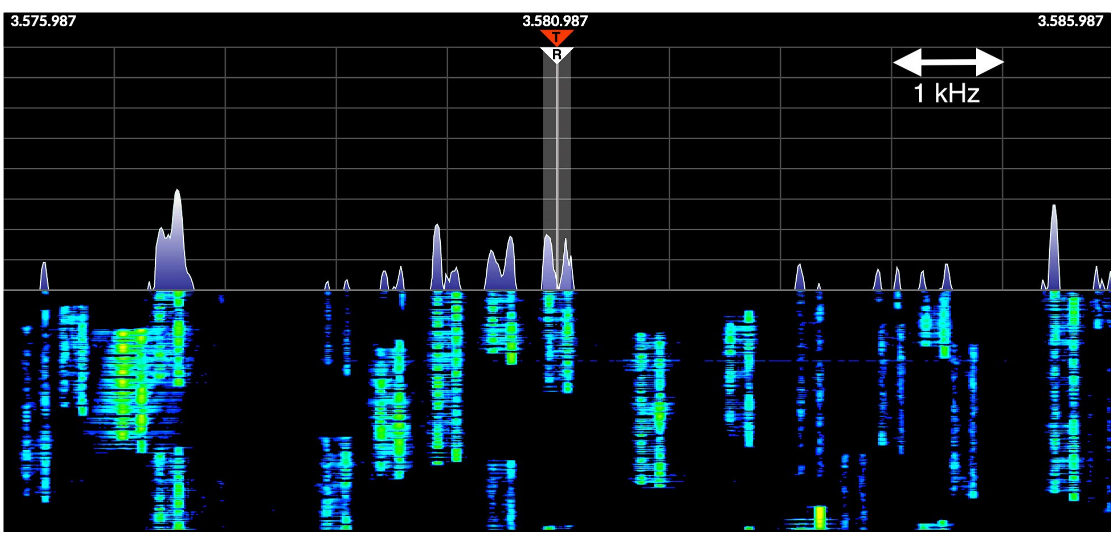


Figure 11-xxii: FSK RTTY signals in frequency-domain (upper half) and waterfall (bottom). Notice each signal's two frequencies representing the two symbols, 170 Hz apart. [EI6LA]

Figure 11-xxii shows many RTTY FSK signals. Note the two frequencies, 170 Hz apart, which represent the two digital RTTY symbols. Most of the shown signals occupy a bandwidth of about 300 Hz.

To reduce bandwidth requirements to a minimum, just like with CW, filtering or pulse shaping of the modulating signal is required when using FSK because any too-sudden shifts of frequency, amplitude, or phase, always cause excessively wide sidebands. See Figure 18-v on page 289 for an example of excessive bandwidth use and interference caused by poor FSK signals.

RTTY, unlike FT8, does not use any error correction techniques. This means that depending on band conditions, noise or fading, the received text may be corrupted, or even completely unreadable. However, because each symbol uses two tones (frequencies) that are slightly apart, RTTY copes with some fading and noise, although nowhere near as well as FT8 or more modern digital modes. Having said that, RTTY is reasonably fast and interactive in comparison to FT8.

11.10 FT8, FSK (J2B, J2D)

FT8 is a digital mode of radio communication that became popular recently.[201] It is not conversational, like RTTY. Instead, it is used to transmit very short, predefined messages containing about 13 characters of text, just enough to transmit call signs, geographical locators, and brief messages such as signal reports. Each transmission takes 13 seconds, and there are four transmissions every minute. It is referred to as a TIME-SYNCED digital mode because all transmissions begin and end at the same time.

FT8 uses FORWARD ERROR CORRECTION. It is a technique that allows for a successful decoding of even somewhat corrupted transmissions. To achieve that, FT8 transmits much additional information in addition to the useful data, almost doubling the size of the information that is being sent.

FT8 data is represented using eight different symbols. The type of modulation is frequency shift keying (FSK) using eight tones (frequencies). It is also referred to as 8-FSK, as the eight tones represent the eight possible symbols.[202] However, even though FT8 is FSK, its signal is not generated directly in the radio using FSK. Instead, FT8 requires special modem software which generates a SUBCARRIER and provides it as audio to the transmitter.[203] First, the sequence of symbols is modulated using FSK by the modem software into an AF subcarrier. This audible signal is subsequently modulated using SSB (USB) in the transmitter. The appropriate ITU designators for FT8 are J2B or J2D, however, it could be also described using other designators. The characters have the following meaning: amplitude modulation single sideband with suppressed carrier (J), one channel digital information using a subcarrier (2), used for automatic (machine) reception telegraphy (B) or data (D).

201 FT8 was created in 2017 by Joe Taylor K1JT and Steve Franke K9AN. FT8 stands for Franke and Taylor 8.

202 Technically, FT8 uses 8-GFSK. This is 8-FSK with the addition of *Gaussian smoothing*, a technique for smoothing the transitions between frequency shifts. It removes the suddenness of the transitions that would cause excessively wide sidebands. In principle, this is similar to the addition of smooth rising and falling waveform edges in CW. It is a form of pulse shaping.

203 WSJT-X is a popular modem software for FT8 and related modes. wsjt.sourceforge.io/wsjtx.html

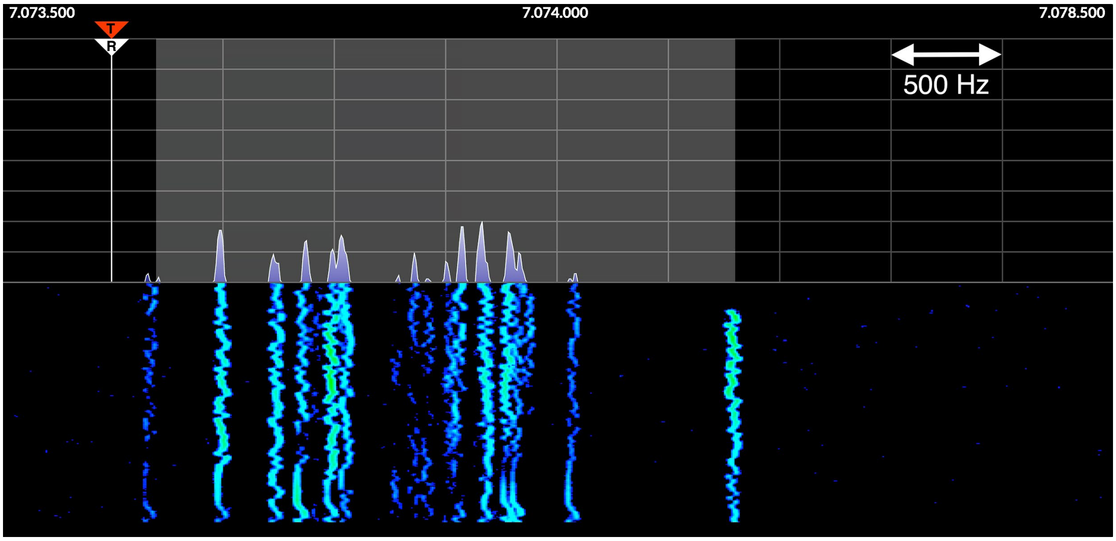


Figure 11-xxiii: FSK FT8 in frequency-domain and waterfall. Each signal is about 50 Hz. The wobbly shape of each signal represents the shifts between the eight tones of each symbol. Grey shows 3 kHz SSB (USB) bandwidth allowing simultaneous reception of all transmissions. [EI6LA]

The speed of FT8, i.e., its symbol rate, is just over 6 baud. The approximate real-world speed of FT8 is about 5 WPM. This may seem slow, however, the high reliability of FT8 even in noisy, low-signal, and fading conditions made it into a popular and surprisingly efficient digital radio communication mode.[204] Because of its low speed and an efficient design, the bandwidth of a single FT8 transmission is only 50 Hz. However, if overdriven, or otherwise distorted, for example by poor audio level set-up in the software, in the computer, or in the transceiver, the bandwidth would grow, and it could interfere with other transmissions. Interestingly, the resilient design of FT8 means that even in case of interference, contacts can be often completed successfully. Figure 11-xxiii shows almost 20 simultaneous FT8 transmissions within a 3 kHz SSB bandwidth, with spare room for more.

11.11 PSK, 2-PSK, 4-PSK (G1B)

PHASE SHIFT KEYING (PSK) is like FSK, except that instead of shifting (changing) the frequency of the carrier it shifts its phase. In its simplest form, shown in Figure 11-xxiv, the phase of the carrier is shifted 180°, i.e., by half of its cycle, see section 5.3 Phase.[205]

204 FT8 was so innovative that many other modes of communication have been created based on its principles, such as the faster FT4, or the email-like JS8CALL, or JT4 and JT65 designed for Earth-Moon-Earth (moon-bounce), or MSK144 used for meteor-scatter communication. Even the low-power WSPR, used for antenna and propagation testing, relies on FT8 principles, but with 4-FSK.

205 This example is oversimplified to show PSK principles. The modulating signal's frequency is a close multiple of the unrealistically low carrier frequency. If the carrier was a much higher frequency, and not a multiple, the plots would not show the half-wave rectification artefacts, and they would be harder to interpret.

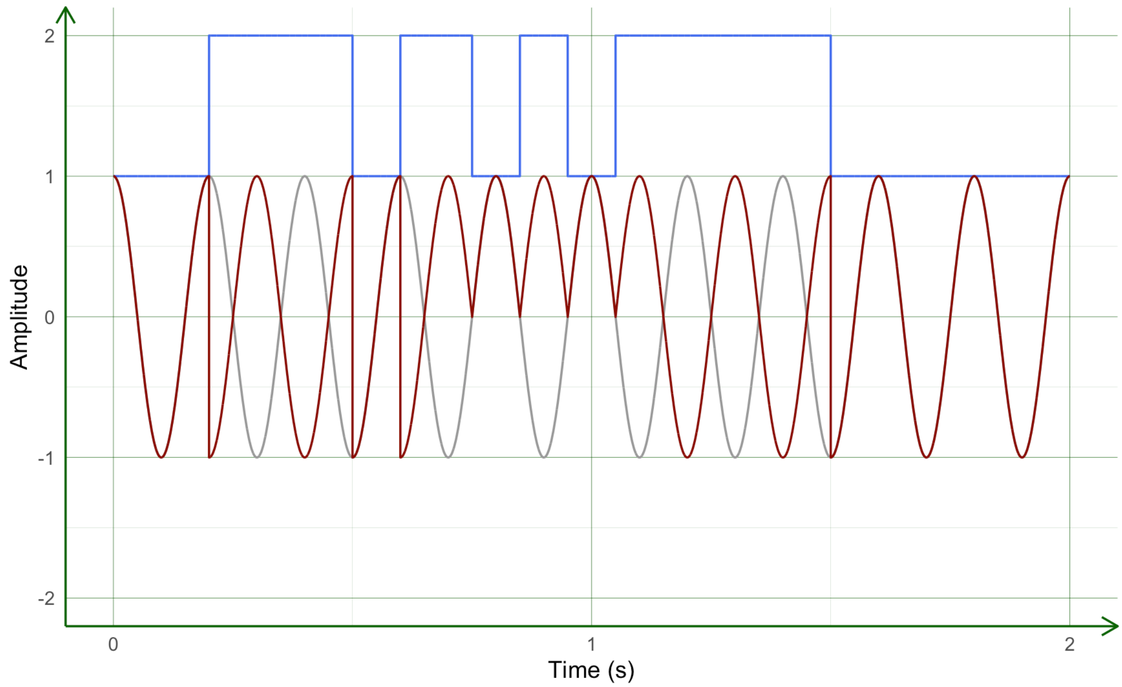


Figure 11-xxiv: Modulated PSK signal (red trace). Modulating signal (blue trace, shifted up for readability), 10 Hz carrier (grey trace). 180° (half-cycle) phase shift. Phase of the carrier shifts each time the modulating signal amplitude changes from low to high and the other way round. [EI6LA]

In that form of PSK, using a 180° shift, there are only two possible changes of the phase. For that reason, it is also known as 2-PSK. There are other forms of PSK which rely on other shifts of the phase. For example, using 90° shifts there are 4 possible changes of the phase. That is known as 4-PSK, and it uses 4 symbols to encode information.

The ITU designator for PSK is G1B: phase modulation (G), single channel containing digital information (1), automatic reception telegraphy (B) .

Modern transceivers include PSK modulation. However, just like FT8 FSK, it is also common to use PSK communication modes with a computer running modem software. Modem software modulates an audio subcarrier using PSK, which is then modulated using SSB (USB) in the transceiver, like in FT8 (see also footnote 200 on page 164 about Audio Frequency Shift Keying (AFSK)). The ITU emission designator would be J2B when using modem software to generate a subcarrier that is transmitted using SSB.

Just like with CW and FSK, it is necessary to either use filtering or to smooth the shape of the modulating signal (pulse shaping) to reduce the suddenness of the changes of the phase and so to reduce the bandwidth requirements to an acceptable minimum.

There are many conversational digital modes of radio communication which use PSK, for example, PSK31.[206]

11.12 Other Modes

There are many other modes of analogue and digital communication than the ones described in this chapter. They include Slow Scan TV (SSTV) used for transmission of images, many other conversational and time-synced data modes, and modes used for telemetry, including weather. There is packet radio with extensive error correcting techniques, which is used to create a radio-based network for connecting computers together. It is also possible to use special digital modes to transmit voice, for example, Digital Mobile Radio (DMR) or System Fusion. Another commercially popular mode is Quadrature Amplitude Modulation (QAM) which is used in WI-FI. They are not part of the exam syllabus.

206 PSK31 is a keyboard-oriented conversational digital mode. It uses 2-PSK with the speed of 31.25 baud. It requires only 100 Hz bandwidth. It is also known as BPSK31. It has no error correction. There is also a related mode, QPSK31, based on 4-PSK. It is slower, but it includes automatic error correction which improves readability in poor band conditions. There are many others.

12 Transmitters

FOUR EXAM QUESTIONS · SECTION A5

RADIO RIG is a generic term for the radio station equipment that includes the primary transmitter and a receiver, and various other peripherals and station accessories. TRANSCEIVERS consist of a transmitter and a receiver combined into a single device, which in amateur use is just referred to as a RADIO, such as the one shown in Figure 12-i. This chapter explains how transmitters work, while receivers are explained in the next one.

Figure 12-i: Hybrid SDR transceiver. Kenwood TS-890S. [EI6LA]

Modern transmitters and receivers extensively use DSP for signal modulation (generation) and demodulation (decoding).[207] With some exceptions, the block diagrams that explain AM, FM, and CW transmitters and receivers shown in this and the next chapter will no longer be found in modern equipment. Unless you are using an old radio, SDR and DSP technologies have replaced those purely analogue designs. On the other hand, the analogue SSB transmitter and receiver design, although with some modifications, is still in use, especially in popular hybrid SDR transceivers. However, a good understanding of all the presented block diagrams is important because they explain the fundamental principles of signal generation. Studying these diagrams yields a better understanding of modulation and other key radio principles, such as the essential role of filters.

Furthermore, the components shown in those traditional block diagrams, such as frequency mixers, power amplifiers, and filters, are still used in modern DSP-based transmitters. Knowing both their original and the modern purpose helps understand how all radios work.

207 As a rule of thumb, commercially available radios introduced after 2005 use DSP for all modulation and demodulation, even if they are hybrid SDR and not fully digital. See the historical footnote 87 on page 67.

Understanding these traditional designs is also important if you would like to build your own transmitters and receivers, which commonly rely on the traditional, analogue electronics, widely available for purchase as kits or components. Because the CEPT amateur radio station licence entitles the holder to build their own transmitters and receivers, understanding those diagrams, even if they differ from commercially sold modern radios, is still a key requirement of the HAREC syllabus.

12.1 Output Power

The OUTPUT POWER is the power of the RF signal generated by the transmitter. There are several ways to measure it. The most important measure of output power for radio amateurs is Peak Envelope Power, (PEP). Amateur radio power limits listed in the Irish regulations specify PEP power measured at the output of the transmitter, or the amplifier if one is used, for almost all of the amateur radio bands discussed in this guide. There are a handful of exception in the Irish regulations where EIRP limit is specified for some of the less frequently used bands, notably for a portion of the 60 m band. Unlike PEP, EIRP considers transmission line losses and gains or losses at the antenna. EIRP is discussed in section 15.20.

The PEAK ENVELOPE POWER (PEP) is the power averaged over an entire, single RF cycle at the crest (the maximum extent) of the modulation. In other words, it is the power that would be produced by the transmitter during one full AC cycle that is so strong that it would reach its maximum amplitude.

Review the time domain plots of different modulation types to see how their amplitude varies over the time, see Figure 11-vi, Figure 11-viii, Figure 11-xviii, and Figure 11-xxi for some examples. Notice that the amplitude of some modulation types is always at its maximum during an active transmission, for example in CW, FM, or FSK, but the amplitude changes in other modes, like in SSB, where it depends on the modulating audio signal.[208]

The AVERAGE POWER can differ from PEP because it depends on the amplitude and the averaging period, which can be short or quite long, several seconds or even minutes, depending on the purpose of the measurement. Assuming a continuous transmission, for some of the modulation types, like FM, there is no difference between the average power and PEP because every modulation cycle uses the maximum possible amplitude. However, for other modulations, such as CW and FSK, there may be significantly long pauses between the characters being sent that would affect the average if the averaging periods were long enough. In SSB, the peak power occurs only for very short time periods so the average power produced by the SSB transmitter will be lower than its PEP.[209]

Duty cycle of a modulation type makes it easier to understand the difference between PEP and average power. It is explained in the next section.

208 To measure PEP of SSB in a way that complies with Irish regulations, a 1 kHz tone must be used for the measurement.

209 This is true for single sideband with a suppressed carrier. The relationship of average power to PEP is more complicated for AM with a full, unsuppressed carrier.

It is common to express RF power both in watt (W) and in dBW, power relative to 1 W, see section 9.3 Absolute Power in . Using dBW is particularly convenient when calculating the effective power emitted by the antenna. It will be discussed in Chapter 15 Antennas.

12.2 Modulation Duty Cycle and Operational Duty Cycle

The MODULATION DUTY CYCLE is an important characteristic of each modulation type. It makes it possible to figure out how much average power is being produced by the transmitter, based on the selected PEP setting.

Knowing the modulation duty cycle is useful for many reasons. It will help you prevent damage to transmitters and amplifiers, because they are rarely rated for operation 100% of the time at maximum PEP. For example, many transmitters can be used at 100% of their rated PEP to transmit natural speech using SSB, a low modulation duty cycle mode, because its time average transmit power is well below the PEP. However, some transmitters and many amplifiers may only allow the use of 50% of PEP when used for digital transmissions, such as RTTY or another FSK. They use high modulation duty cycle modes, meaning that their time average transmit power can equal the PEP. Exceeding those design limitations will eventually cause damage to expensive components, such as the final amplification stage transistors or valves.

Another important reason for understanding modulation duty cycles is to know if the average power of your RF emissions is within the exposure safety guidelines. This subject is explained in detail in section 19.8.5 Estimating and Modelling RF Field Strengths and Exposure.

The MODULATION DUTY CYCLE is a percentage.[210] It depends on the proportion of time during which the transmitter is producing the maximum output power for a given mode. It does not depend on how you use a given mode, but only on the chosen mode modulation type.

For example, in a continuous CW transmission the full power of the carrier wave is only produced when the Morse key is pressed down, but not during the gaps between the dits and the dahs. The duty cycle of CW is 40% because there is no power being transmitted for the remaining 60% of the time.

Modulation duty cycle of SSB used to transmit normal, unprocessed speech is only 20%, but it becomes higher when using audio compressors.

Table 12-A shows the modulation duty cycles that you need to know. Please note that all the relevant modulation types and modes have been explained in Chapter 11.

There is another duty cycle that is worth knowing. The OPERATIONAL DUTY CYCLE describes what percentage of time the operator is transmitting in a given averaging period, such as a 6-minute period commonly used for RF safety compliance evaluation purposes. For example, unless reading lengthy news on the air, it is

210 Duty cycle can be also expressed as a number between 0 and 1, in which case it is known as a *duty factor,* or a *mode duty factor,* or as *mode factor.* It is easy to understand. For example, if a duty cycle of a mode is 42% its duty factor is 0.42. Modulation duty cycle of 100% would be the same as mode factor of 1, etc. You will find references to mode factors in various radio safety-related publications.

typical to speak for only 50% of the time and to listen for the rest of the time. This operational duty cycle may be considered when evaluating RF exposure guideline limits for some of the modulation modes, see footnote 375 on page 306.

Table 12-A: Modulation duty cycles of common modulation types

Modulation type	Duty cycle
AM (A3E)[211]	up to 100%
CW (A1A)	40%
Digital modes[212]	up to 100%
FM (F3E)	100%
SSB (J3E) uncompressed	20%
SSB (J3E) compressed with speech processing to increase the perceived volume	40%

Unlike the modulation duty cycle which only depends on the chosen modulation, the operational duty cycle depends on the operator and their habits.

12.3 Output Impedance

Maximum power is delivered to the transmission line and the antenna (the load) when the OUTPUT IMPEDANCE of the transmitter matches the load impedance.

Commercial transmitters and amplifiers are designed to match the load impedance of 50 Ω, which matches commonly used coaxial transmission lines and other equipment. To achieve that, transmitters contain an OUTPUT NETWORK[213] which is a circuit designed to match the nominal load impedance of 50 Ω to the output impedance of the final amplifier, without producing distortions.

Interestingly, this does not mean that the actual output impedance of modern transmitters is necessarily the same 50 Ω. Modern transmitters and amplifiers are designed for an optimum undistorted load impedance which can be different from that which would present an ideal match to the amplifier's output impedance. Perhaps surprisingly, such a carefully chosen yet apparent impedance mismatch can help improve the balance between the goal of efficiency and the goal of maximum undistorted output power transfer. Real-world designs must keep any distortions and

211 There are many ways to generate AM (A3E) and they use very different duty cycles.

212 Even though the transmitter is producing full power when generating digital mode signals, such as RTTY FSK or PSK31, the average power transmitted by some of the modes, such as FT8, is lower, when averaging over a typical 6-minute period. The modulation duty factor of FT8 is only 42%, and not 100%. The reason for that is that FT8 is a time synchronised communication mode, and it does not transmit during the entire one minute. Your equipment may have enough time to cool down between the transmissions, and it also reduces the RF emissions, compared, for example, to RTTY.

213 The output network is also known as the *Pi tank* because of the similarity of its popular design to that of some LC filters.

non-linearity minimised, keeping within the amplifier's design class and not producing interference-prone spurious emissions, splatter, clicks, etc.[214]

Essentially, the output impedance of real-world power amplifiers, and transmitters that contain them is not the same as their nominal load impedance because of efficiency and signal quality reasons. Nevertheless, their typical NOMINAL OUTPUT IMPEDANCE, which is the impedance of the load that they expect to be connected to, is 50 Ω.

12.4 Efficiency and Output Power

The EFFICIENCY of a transmitter is directly related to the efficiency of the amplifiers that it contains, especially the efficiency of the final stage power amplification. As remarked in sections 12.6–12.10, the class of the final amplifier determines its efficiency. Depending on the used class, the efficiency of a transmitter varies between 25–80%, commonly 60%. Higher efficiency means more useful RF output and less wasted heat.[215] See sections 10.7.1 Amplifier Characteristics and 10.7.2 Classes of Power Amplifiers.

Real-world transmitters and their amplifiers need to balance goals of amplification efficiency with the goal of an efficient, undistorted transfer of power to the transmission line and the antenna. Because every amplification class other than class A involves some acceptable level of non-linearity, balancing those goals usually requires a different output impedance than nominal load impedance, as mentioned in the previous section.

12.5 Problems Affecting Transmitters

The FREQUENCY STABILITY is the ability of a transmitter to maintain the same, precise frequency over time, without drifting. Traditional, analogue designs are susceptible to heat and mechanical considerations. Digital designs usually offer better frequency stability.

A NON-LINEARITY happens when an amplifier introduces a distortion. Since every type of a transmitter has an internal amplifier, amplifier problems affect all transmitters. By far, the main cause of non-linearity is an overdriven amplifier, perhaps because the transmitter is fed with an excessively high input signal. Loud audio, and poorly adjusted digital signal levels coming from a computer, or an overactive

214 Non-linearities are not equally bad. The ones that must be carefully avoided in the design and operation of transmitters and their power amplifiers are those that cause output signal's amplitude distortions, even after filtering, because they cause harmful interference: splatter, key clicks etc.

215 Recall from 10.7.1 that efficiency determines how much of the supplied power becomes the useful output power, which in a transmitter would go to the antenna. The rest is lost to heat. With efficiency of 60% that would mean 40% of the energy consumed by the transmitter becomes wasted as heat. To produce 100 W of output power requires at least 166 W of supplied power. 40% of 166 W, i.e., 66 W of that power is used to heat the room. There are other components in a transmitter that will also require power that is lost to heat, such as power supplies, the electronics driving the DSP and SDR, the display and indicators, and other inefficiencies inherent to all electronics. Overall, the efficiency of the transmitter will be always lower than the efficiency of its final amplifier.

ALC can cause significant overdriving of an amplifier. If the non-linearity is significant, it will cause excessive bandwidth use, splatter, and other types of harmful interference. Section 18.2 Transmitter Distortion and Spurious Emissions explains the problems caused by amplifiers, including key clicks, splatter, and spurious emissions.

12.6 CW Transmitter

As explained in section 11.8, CW modulation, A1A, uses OOK, that is, turning the amplitude of the carrier on and off using a Morse key. It is a form of ASK. A block diagram of a simplified CW transmitter is shown in Figure 12-ii.

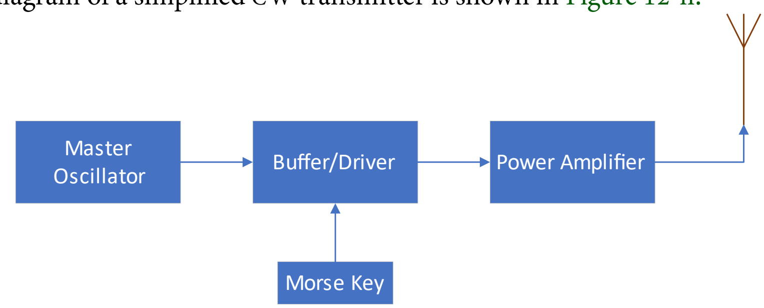


Figure 12-ii: CW transmitter block diagram. [EI9ILB]

Such a simple design of a CW transmitter requires appropriate low-pass filtering to avoid causing key clicks and splatter. Key clicks would lead to an unacceptably excessive bandwidth use caused by too sudden switches between the on and off states of the carrier signal. See section 11.8.2 CW Modulated Signal for more information about other ways to shape the resulting waveform to avoid such issues. See section 18.2 Transmitter Distortion and Spurious Emissions for more information about key clicks and splatter.

12.6.1 CW: Master Oscillator

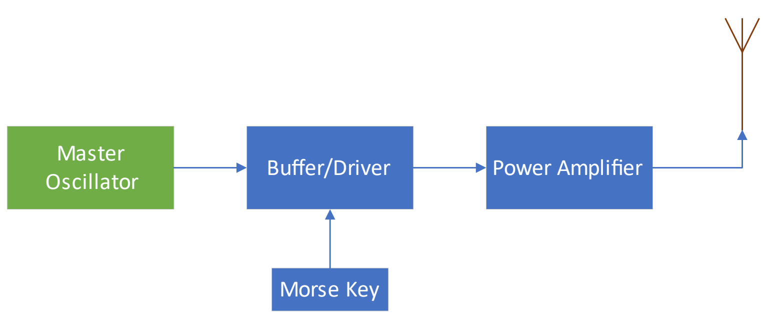


Figure 12-iii: CW transmitter: master oscillator. [EI9ILB]

The MASTER OSCILLATOR generates the carrier wave as a sinusoidal AC at the required frequency. See also section 8.6 Oscillators.

Another problem that can affect analogue CW transmitters is CHIRP. It happens when the frequency of the transmission varies when the Morse key is pressed. It sounds like a bird chirping. It can be caused by poor power supply regulation, whose voltage drops while the key is pressed, affecting the master oscillator, or poor oscillator buffer/driver design. It is unheard of in digital transmitter designs, but can be occasionally heard from battery operated, portable analogue CW transmitters.

12.6.2 CW: Buffer/Driver

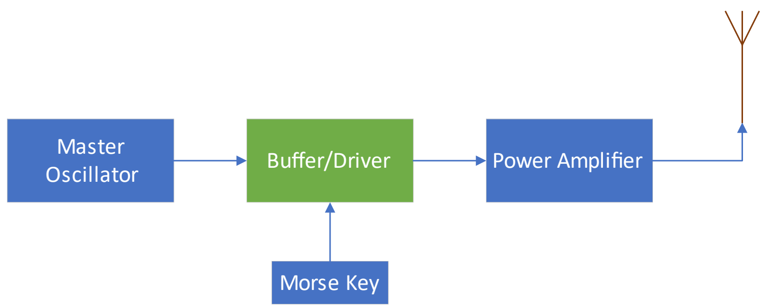


Figure 12-iv: CW transmitter: buffer/driver. [EI9ILB]

The Morse key, such as the straight key shown on the left of Figure 11-xvi on page 160, can be thought of as an on-off switch. When the operator closes the switch, the carrier wave, generated by the master oscillator, should be transmitted.

The BUFFER/DRIVER isolates the master oscillator so that the oscillator continuously provides a stable frequency output. If the master oscillator was keyed directly by the Morse key, the on/off keying would affect the frequency stability of the oscillator and eventually result in an unstable transmitter frequency output to the antenna. Further, if the power amplifier was connected directly to the master oscillator, it could draw excessive power from it also causing it to become unstable or to even to stop oscillating.[216]

12.6.3 CW: Power Amplifier

The master oscillator generates low voltage, low current, and therefore, low power AC. Such signal would not be powerful enough for the transmission from the attached antenna. The POWER AMPLIFIER increases the power of the resulting AC to the required level, such as 5–100 W. A class C amplifier may be used for CW. Even though class C has poor linearity it offers high efficiency, see section 10.7.2 Classes of Power Amplifiers. Careful filtering, to avoid key clicks and splatter, is necessary.

216 Another name for this problem is *pulling* because the power amplifier would pull too much power from the oscillator in the absence of a buffer that isolates those components and provides the necessary minimum power to the amplifier.

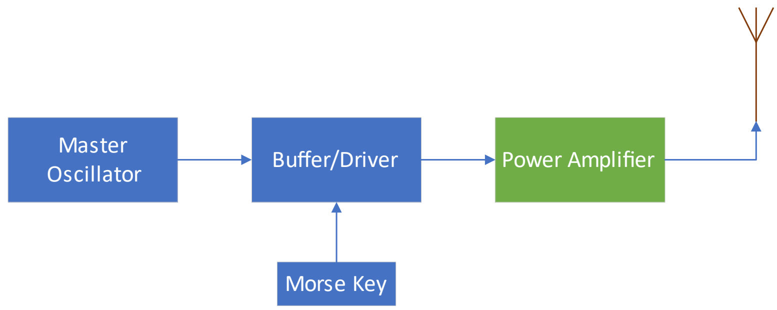


Figure 12-v: CW transmitter: power amplifier. [EI9ILB]

This power amplifier is internal to the transmitter. If higher power is required, an external power amplifier may be used, see 12.12 High Power Linear Amplifiers.

12.7 SSB Transmitter

SSB transmitters are important. J3E modulation is used in amateur radio for phone (voice) communication. It is also widely used for the transmission of many digital modes, such as FT8 (J2B, J2D) which use modem software running on a computer to encode digital information as an audible AF subcarrier, see section 11.10. Perhaps even more importantly, the design principles of SSB transmitters, notably the mixer, also apply to some hybrid design SDR to transmit signals modulated using DSP.

SSB (J3E) is AM with one of the two sidebands removed and the carrier suppressed. It is explained in detail in section 11.6.

A block diagram of a simplified SSB transmitter is shown in Figure 12-vi. The main principle of its operation is to generate SSB signal at a fixed, low IF, and then to translate it to the desired output frequency. To do that, the output from the VFO is combined in the mixer with the IF SSB signal to translate it to the desired output frequency.

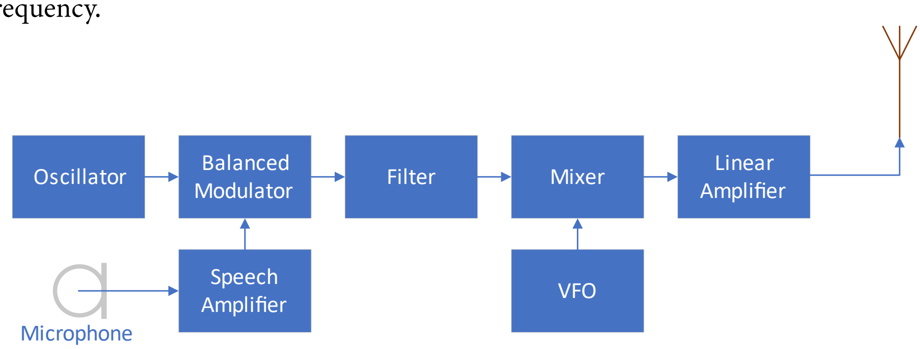


Figure 12-vi: SSB transmitter block diagram. [EI9ILB]

12.7.1 SSB: IF Signal Generation

The oscillator in an SSB transmitter produces AC at a fixed, low frequency. The speech amplifier is an AF amplifier that increases the power of the audio signal coming from the microphone or from a computer's sound output to the level matching the oscillator. The speech amplifier may also provide additional audio processing features, for example to adjust the level of bass/treble. It may also provide audio compression, which increases the perceived volume of quieter parts of speech to make it sound stronger. Those features should only be used for speech and should be switched off when transmitting digital signals, such as FT8, in order not to distort data.

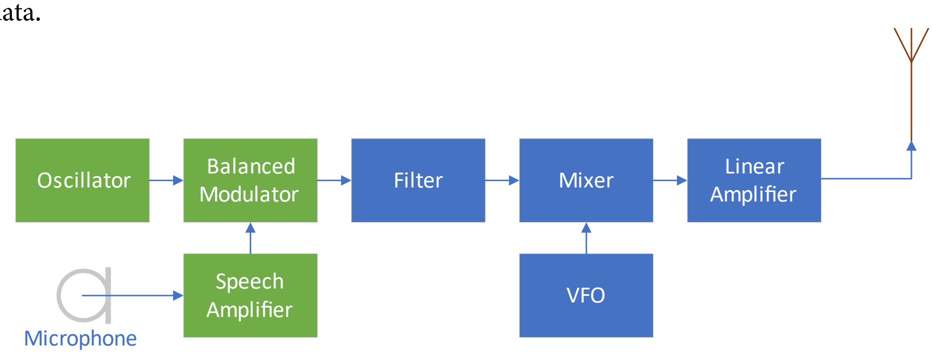


Figure 12-vii: SSB transmitter: IF signal generation. [EI9ILB]

The BALANCED MODULATOR impresses the audio signal onto the low frequency AC using AM. The resulting IF signal consists of both sidebands, but without the carrier whose frequency is that of the oscillator.

12.7.2 SSB: Filter

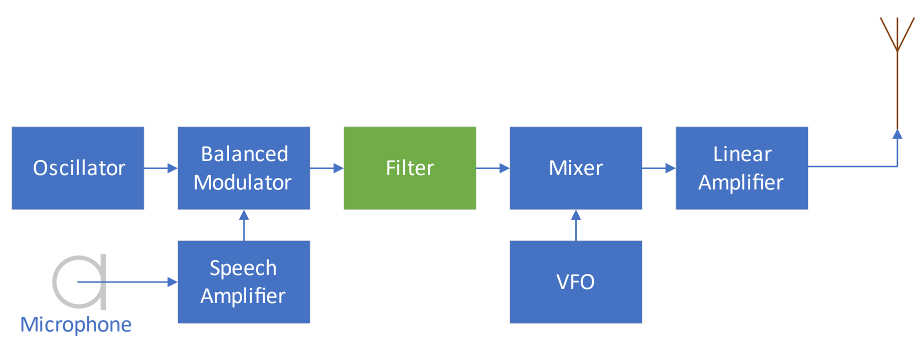


Figure 12-viii: SSB transmitter: filter. [EI9ILB]

The FILTER in an SSB transmitter fulfils the key function that defines this type of modulation: it removes the unwanted sideband. The result is IF SSB (J3E) single sideband signal with suppressed carrier. The choice of the sideband, lower (LSB) or upper (USB) is usually made using a control on the front panel of the transmitter.

Typically, it is a crystal band-pass filter. Its characteristics determine the bandwidth of the signal. Typical filter bandwidths used for SSB are between 1.8–2.4 kHz.

12.7.3 SSB: Mixer

The MIXER is responsible for translating the low IF to the desired signal frequency. It mixes the IF with a pure sine wave signal generated by the VFO. As is always the case when two signals are mixed, the result consists of frequencies that are the sum and the difference of the mixed frequencies, and their harmonics.

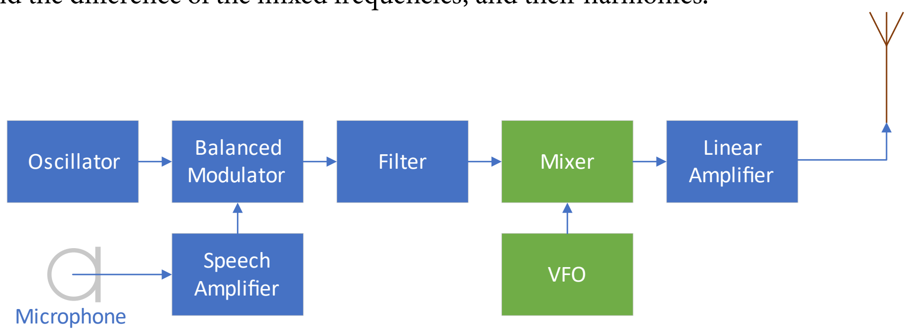


Figure 12-ix: SSB transmitter: mixer. [EI9ILB]

In other words, the mixer translates the frequency of the already-modulated audio signal to frequencies that are the sum and the difference of the frequency of the VFO and of the oscillator, and their harmonics. The mixer's circuitry contains another filter (not shown on the block diagram) that passes only the signal at the desired frequency and removes all the remaining ones.

12.7.4 SSB: Linear Amplifier and Automatic Level Control (ALC)

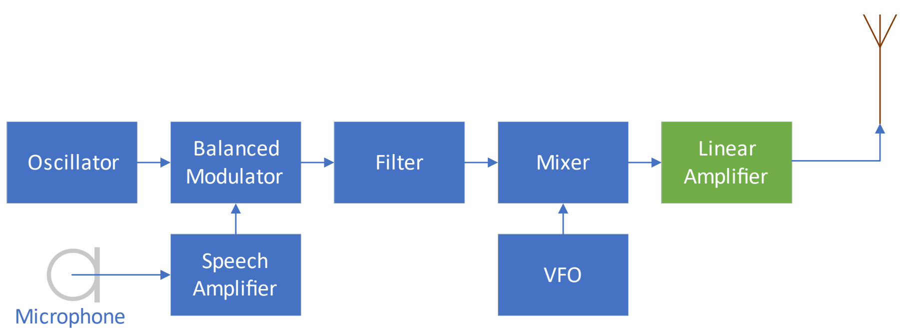


Figure 12-x: SSB transmitter: linear amplifier. [EI9ILB]

Just like with the CW transmitter, the voltage, current, and therefore, the power of the AC that represents the signals generated by the SSB transmitter is very low and

insufficient to be transmitted by the antenna. The LINEAR AMPLIFIER is used to increase its power to the desired level, usually 5–100 W.[217]

Linear amplifiers contain some of the most expensive components of the transmitter. They are easily damaged by excessive heat. It is important to be aware of the amplifier power ratings and not to exceed them, especially when using high duty cycle modulation modes, such as digital modes, as the heat can become destructive.

Unlike in a CW transmitter, however, the amplifier must be linear. Any significant non-linearity would cause both harmonic and intermodulation distortion (IMD) which would result in a distorted audio and excessive bandwidth use, and which can cause splatter, see section 18.2 Transmitter Distortion and Spurious Emissions.

As explained in section 10.7.2 Classes of Power Amplifiers, class A offers great linearity but low efficiency of only up to 30%. Class AB offers good enough linearity and an increased efficiency of up to 60%.

Overdriving an otherwise linear amplifier with excessively strong signals will cause non-linearity, also leading to distortion, splatter, and excessive bandwidth use. This may not always be obvious to the operator, especially when using SSB transmitters for digital modes. Correctly setting the level of the audio subcarrier coming from a computer is necessary to prevent non-linearity.

The AUTOMATIC LEVEL CONTROL (ALC) is a feedback circuit from the linear power amplifier which seeks to avoid overdriving it with excessively high audio levels. When ALC activates, it automatically turns down the level of incoming audio. There is usually an ALC meter on the front panel of the transmitter. Seeing some ALC activity is normal when transmitting voice, although too much will cause you to sound rough and unnatural. As a rule of thumb, no ALC activity should be seen when transmitting digital information using SSB and other modes.

If using an external amplifier, it is preferable not to rely on ALC because it can be a new source of significant non-linearity. It is better to monitor the signal and adjust the drive levels so that no overdriving happens.

12.8 FM Transmitter

FM (F3E) is frequency modulation. It is primarily used on VHF, UHF, and higher bands for phone communication. It is explained in section 11.7 FM (F3E).

The FM transmitter is relatively simple. Its simplified block diagram is shown in Figure 12-xi. The principle of operation shown in this diagram generates FM signal as a low IF which is then multiplied to the required frequency. Alternatively, the IF could be mixed with a VFO to obtain the desired frequency just like in an SSB transmitter.

217 Just as in the CW transmitter, there would be a buffer/driver just before the amplifier, however, it is not shown in these simplified diagrams.

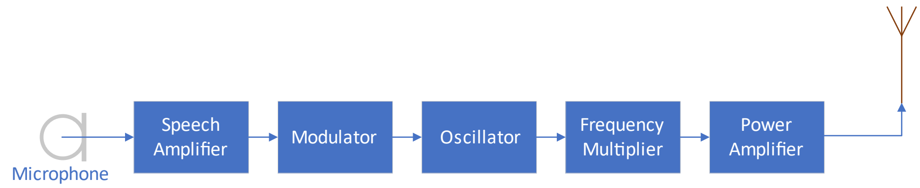


Figure 12-xi: FM transmitter block diagram using a frequency multiplier. [EI9ILB]

12.8.1 FM: IF Signal Generation

The speech coming from the microphone is amplified and processed just like in an SSB transmitter. The MODULATOR together with the oscillator produces a frequency modulated signal.

The frequency of the oscillator depends on the output frequency chosen by the operator, but it is not equal to it. The oscillator usually runs at a lower frequency than the output frequency of the power amplifier, because frequencies in the VHF and UHF bands, where FM is popular, are difficult to produce directly from crystal oscillators.

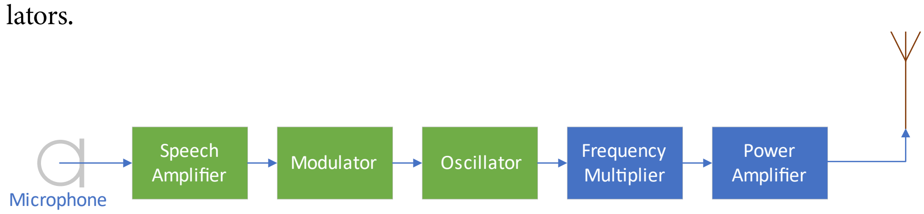


Figure 12-xii: FM transmitter: IF signal generation. [EI9ILB]

The oscillator frequency is varied by the modulating signal, which in this case is the audio from the microphone. The modulator works by causing the frequency of the oscillator to vary in proportion to the amplitude of the audio. This principle of FM is explained in section 11.4.2.

12.8.2 FM: Frequency Multiplier

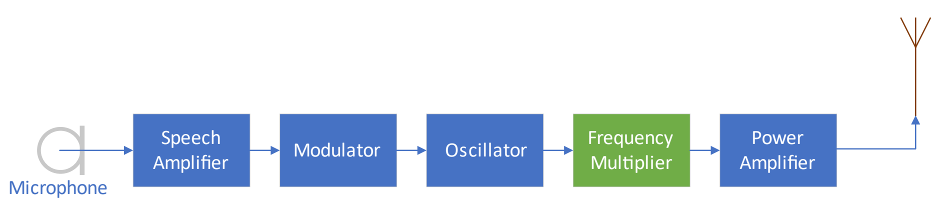


Figure 12-xiii: FM transmitter: frequency multiplier. [EI9ILB]

The choice of oscillator frequency is such that it is a fraction of the power amplifier output frequency, therefore a FREQUENCY MULTIPLIER must be used to attain that final frequency. Frequency multiplier is a low power amplifier whose output is tuned

to a fixed harmonic, often the 3rd, of the input signal.[218] For example, if the output frequency is 30 MHz, then the oscillator frequency should produce 10 MHz. More modern FM transmitters also use a FREQUENCY CONVERTER instead of a multiplier.

Frequency multipliers and frequency converters are also used in some hybrid SDR transmitters.

12.8.3 FM: Power Amplifier

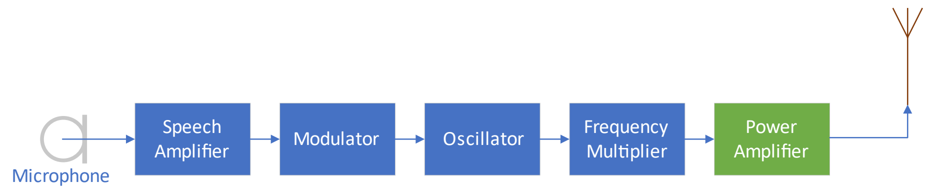


Figure 12-xiv: FM transmitter: power amplifier. [EI9ILB]

Just like in a CW and an SSB transmitter, the low power AC generated so far must be increased in power before it is transmitted by the antenna. Unlike in an SSB transmitter, the power amplifier of an FM transmitter does not have to be very linear because the amplitude of the modulated signal is not as important in FM as it is in AM. Class C amplifiers can be used as FM power amplifiers to achieve high efficiency.

12.9 Digital Modes

Digital modes of radio communication are very popular.[219] Several of them have been introduced in Chapter 11. Sections 11.8–11.11 explain how the most popular digital modes work.

More advanced, modern, commercially sold transceivers can generate some digital signals internally, for example, RTTY FSK from pre-programmed, stored messages, or by using a Universal Serial Bus (USB) keyboard directly plugged into the transceiver. This is possible because, like much modern electronics, they are built like a computer and internally they rely on DSP and SDR. Many modern radios can also decode some received digital signals, such as RTTY FSK, PSK, and CW.[220] However, that is not the most common way of using digital modes at present. Instead, Figure 12-xv shows the widely used method to transmit and to receive digital information using a computer and a software modem.

218 A frequency multiplier is a low power amplifier that is overdriven, on purpose, to behave in a non-linear way and to produce strong harmonics. Several frequency multipliers can be used in a cascaded manner, offering a range of much larger increases of a frequency.

219 At the time of writing, January 2024, the most popular day-to-day amateur radio communication mode is the FT8 digital mode, according to log analysis data provided by Club Log, clublog.org. CW holds the second place. Phone modes appear in the third place. Outside day-to-day use, the traditional modes, CW, phone, and RTTY, are more popular during radio contests than the modern digital ones.

220 While the decoding of computer-generated digital signals, such as FSK and PSK, can be quite accurate, automatic decoding of manually sent CW is still imperfect. Often, human ear and brain are much better at decoding weak and noisy CW signals than decoders.

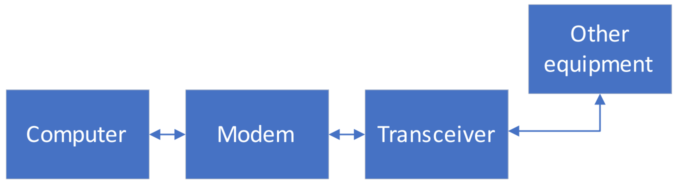


Figure 12-xv: Digital station using a software or a hardware modem. [EI9ILB]

A computer runs MODEM SOFTWARE, such as the popular WSJT-X suite used for FT8 and WSPR.[221] This software produces an AF subcarrier.[222] This audible AF subcarrier is fed to the transmitter using standard audio cables or using a USB computer connector supported by modern transceivers.[223] The transceiver uses SSB to modulate the AF subcarrier at the required frequency and sends it to the antenna.

This popular approach requires careful adjustment of the audio levels of the AF subcarrier generated by the software modem so as not to overdrive the transmitter's amplifier. That could cause distortions that would degrade the transmitted signal and reduce the ability of the receivers to decode it. Similarly, the level of the audio received from the transceiver, and being fed to the modem, should be carefully adjusted. If it is too high, it will cause signal clipping and distortion in the digital modem, making decoding hard or impossible.

It is also possible to use hardware modems and more complex digital interfaces to generate digital signals, either as AF subcarrier, or for direct keying of the transmitter.[224]

12.10 Modern Transmitters and SDR

The fundamentals of DSP have been discussed in Chapter 6. Make sure to review the explanation how the basic DSP and SDR components work, in particular, the ADC, in section 6.3, the DAC, as well as DDS, in section 6.4, and the difference between hybrid and fully digital designs, section 6.5.2.

221 There are many software modems other than WSJT-X, such as: fldigi, JTDX, JS8CALL, MMTTY, 2Tone, and others. They differ in the choice of modes they support, how they perform when conditions are poor, and what computers they run on – many support Linux/UNIX, macOS, and Windows.

222 You can hear this subcarrier as beeps and other electronic sounds which are reminiscent of fax machines or dial-up modems that were popular in the 20th century. You can hear it when tuning a receiver in SSB mode across frequencies used by the digital modes. Listen to the samples at www.w1hkj.com/Modes/index.htm and www.sigidwiki.com/wiki/Category:Amateur_Radio

223 When connecting a modern transceivers using a USB cable, it appears as a pair of virtual audio input and output devices on the computer. They act as if you connected an additional microphone and a speaker to the computer. The virtual microphone passes audio from the receiver to the software modem running on the computer. The virtual speaker delivers the AF subcarrier to the transmitter. These virtual devices are often named *USB Audio Codec*.

224 Some modem software does not generate AF subcarriers. Instead, it directly *keys* the transmitter to generate digital signals, such as computer-generated CW, or FSK used for RTTY. Such keying software and hardware is only useful for the transmission rather than the reception of data. For example, reliable RTTY communication often uses a hardware device for directly keying the FSK transmitter, and a software modem to decode the received audio subcarrier.

Regardless of whether the modern radio is a hybrid SDR or fully digital, it uses DSP to generate the modulated signal. This enables a significant level of control over its quality. For example, the CW waveform generated this way can be shaped, in software, to have the optimal rise and fall time to ensure maximum signal clarity yet without key clicks, splatter, or other distortions, see section 11.8.2. Typically, DSP generates a fully modulated signal at a low IF.[225] The IF is then translated to the required frequency using different methods, even using a traditional SSB transmitter.

Current SDR and DSP technologies have limitations. Software alone cannot be used as a power amplifier, or to filter strong out-of-band signals. While this may change in the future, all modern transmitters rely on traditional, analogue circuits for final stage power amplification and for both incoming and final filtering.[226]

12.10.1 Fully Digital Transmitter with RF DDS

Although this is not yet the most popular approach, transmitters are becoming fully digital. Not only is the IF generated by the DSP, but even the process of upconverting the IF to the required frequency is done digitally in this type of an SDR transmitter. It uses computerised integrated circuits for the up conversion.

The currently most advanced approach uses SDR to modulate the signal directly at the desired high frequency, making the DSP work at RF. A simplified block diagram of such a transmitter is shown in Figure 12-xvi.

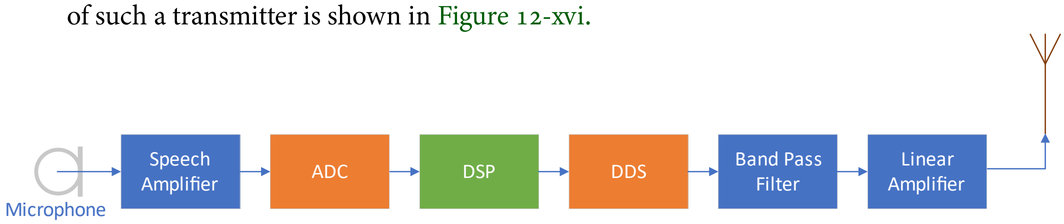


Figure 12-xvi: Fully digital SDR transmitter with RF DDS. [EI9ILB]

DSP receives digital signal, such as digitised audio from the microphone or from another input, after it has been amplified, just as in pure analogue transmitters. DSP performs any required signal improvements, such as audio compression. Most importantly, however, DSP modulates the input signal using the selected mode, such as AM, SSB, FM, CW, FSK etc. The output from the DSP is digital data (a sequence of numbers) representing RF signal.

The digital RF data needs to be converted into AC. DDS is not the only available technology, but it is a common approach for synthesising both IF AC and RF AC from its digital representation. It was explained in section 6.4. The block diagram shows the DSP and the DDS working directly at RF. The output from the DDS is AC at RF.

225 Usually 36 kHz, or in the range of 12–192 kHz.

226 Digital filters can be very advanced. They are able to achieve high quality results with steep, sharp transitions, and good performance at a cost lower than equivalent quality analogue, electronic filters. However, they cannot yet output high power AC in an economical design. DSP uses digital filters on a digitised, low power signal that has been traditional pre-filtered to remove out-of-band components. See section 8.4.3 Digital Filters.

If the DSP was operating at a lower IF, a DDS could include a digital frequency upconverter, and produce the AC at RF.[227] Alternatively, it could use the hybrid design, discussed in the next section.

An analogue band-pass filter removes any remaining by-products of the digital to analogue conversion and enforces the correct bandwidth of the generated signal. Its design may be a little more complex than in a traditional transmitter because it must serve the needs of different modulation schemes and their different bandwidths.

Just as in analogue designs, the AC of the signal generated so far has low voltage, low current, and therefore, low power. The linear amplifier increases the power to the level required by the operator, such as 5–100 W, before it reaches the transmitting antenna. Because the hybrid transmitter can generate all types of modulated signals, the amplifier must be linear. Class A and the more efficient, and more popular, class AB are commonly used. That linear power amplifier is a traditional, electronic circuit. It is not yet possible to perform amplification using software alone.

12.10.2 Hybrid SDR Transmitter with IF DDS

Hybrid SDR transmitters are very popular. They use traditional analogue circuitry to translate the IF to the required RF. Often, there are several stages of frequency conversion in hybrid SDR transmitters. A block diagram of a simplified hybrid transmitter is shown in Figure 12-xvii.

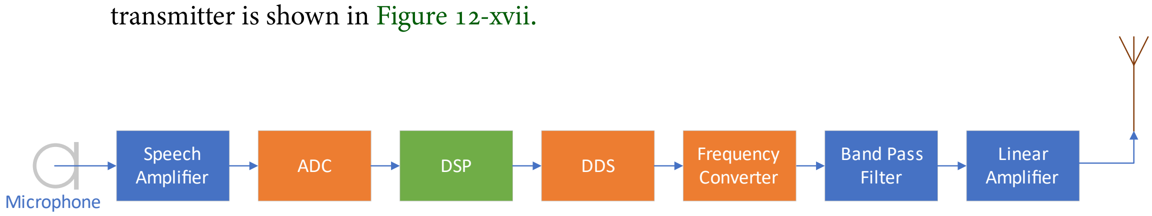


Figure 12-xvii: Hybrid SDR transmitter with IF DDS. [EI9ILB]

The main difference between the operation of this transmitter and the one explained in the preceding section is that the DSP and the DDS work at a lower IF rather than the higher RF.[228] The synthesised, modulated AC produced by the DDS is at IF.

A frequency converter, or a mixer, or a frequency multiplier, is used to translate the IF to the required RF. It is an analogue electronic circuit, similar to those found in traditional FM and SSB transmitters.

The function of the analogue band-pass filter and the analogue linear amplifier is identical to that explained in the previous section.

This is one of the most popular transmitter designs in current use, although it is likely to be replaced by fully digital designs in the future.[229]

227 This is how ICOM IC-7300 and IC-7610 work.

228 The digital data is a sequence of numbers. Digital IF is sometimes called *pseudo IF* to differentiate it from analogue AC IF.

229 This is how Elecraft K3, Kenwood TS-890S, Yaesu FT-DX3000, FT-DX10, FT-DX101 work, amongst many others. This approach has been common since 1995. See footnote 87 on page 67.

12.11 Transverter

A TRANSVERTER is a transmit and receive frequency converter used to convert an entire transceiver for use on a different band. For example, a 28 MHz to 144 MHz transverter can be used to allow a HF transceiver to operate on VHF. The transverter converts both the receiver and the transmitter to work on the other band.

A transceiver connected to a transverter will usually retain all its functionality on the converted band and should support all the communication modes that the transceiver is capable of.

12.12 High Power Linear Amplifiers

As introduced in section 10.7.6 RF Amplifiers, it is possible to use an external RF high power linear amplifier to further increase the power of the output signal.

For example, a small, portable, battery-operated, low-power QRP[230] transmitter may generate signals with only 1–10 W of power. When brought back to the fixed, home station its power output could be increased significantly by connecting it to an external, mains supply, high power linear amplifier. All power levels, such as 400 W, can be achieved this way.

An external high-power amplifier used for these purposes must be of high quality, and appropriately linear, if it is going to be used with a variety of communication modes and modulation types. Otherwise, it is likely to introduce significant distortion, making some transmissions difficult to receive and decode, and causing significant, harmful interference.

Never overdrive an external high power linear amplifier, even a high quality one, as it will become non-linear, and cause distortion and harmful interference. See section 18.2 Transmitter Distortion and Spurious Emissions for examples of harmful interference.

! Observe safety precautions when working on high power amplifiers, as voltages are lethal. Do not operate them without covers or with shields removed for reasons of electrical safety and to prevent harmful exposure to intense EMF. See sections 19.4.5 Valve Equipment and High Voltage Power Supplies, 19.4.6 Adjusting Live Equipment, and 19.8.6 Interior of Transmitters and Power Amplifiers.

12.13 HF Station

A complete HF station is shown in Figure 12-xviii. It includes all the required components, such as a Standing Wave Ratio (SWR) bridge and a low-pass filter, the recommended components, such as the dummy load (see 17.10) and a switch, and optional components, like the high-power linear amplifier.

230 QRP commonly stands for low-power operation. Q-Codes are introduced in Chapter 26.

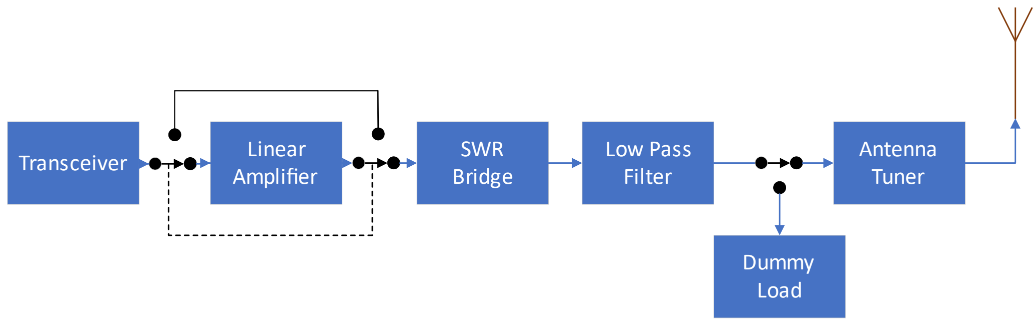


Figure 12-xviii: HF station. [EI9ILB]

The SWR bridge indicates if there is an impedance mismatch between the antenna system and the transmitter. Ideally, the SWR should be close to 1:1, indicating a good impedance match yielding an optimal power transfer from the transmitter to the connected transmission line and the antenna. SWR is discussed in 14.9 Impedance Matching and Transformation and the SWR meter in 17.2 SWR and Power.

An ATU is used to match the impedances of the devices connected to it. If it is installed between the transmitter and the transmission line, it can match the combined impedance of the attached transmission line and the antenna to the nominal output impedance of the transmitter. Or, preferably, if installed between the transmission line and the antenna it can match the feed point impedance of the antenna to the characteristic impedance of the transmission line. In either case, it aims to bring the SWR as close to 1:1. See section 14.10 Antenna Tuning Units.

The low-pass filter cuts off frequencies above 30 MHz suppressing any remaining harmonic spurious emissions.

A dummy load is used to test and tune the components without transmitting (radiating) any unnecessary signals. Dummy loads are also very useful when troubleshooting, and when performing measurements, see section 17.10 Dummy Load. Make sure it is sufficiently rated for the power level generated by your transmitter and any amplifier. If you engage the transmitter for longer than the rated duration and power, the dummy load will become very hot and can leak or burn.

The dotted lines surrounding the linear amplifier indicate that it can be switched into or bypassed by flipping a switch. Modern linear amplifiers automatically engage such a bypass when turned off.

13 Receivers

FOUR EXAM QUESTIONS · SECTION A5

Transceivers consist of a transmitter and a receiver combined into a single device, a radio. This chapter explains how receivers work. Transmitters have been discussed in the previous chapter.

The purpose of a radio receiver is to acquire an RF signal, containing information in the form of a modulated signal, and to process it into either an audible (AF) sound, or into another form, such as text, data, image, or a video, depending on the chosen communication mode.

A good receiver should have good SENSITIVITY to resolve weak (quiet) signals satisfactorily, without introducing noise. It should also have good SELECTIVITY to separate the required signal from unwanted or interfering ones. These characteristics are further discussed in section 13.7. A receiver must:

1 AMPLIFY weak signals from the antenna
2 SELECT the required signal
3 FILTER out unwanted signals and noise
4 DEMODULATE (detect, decode) the underlying signal containing the information of interest
5 AMPLIFY the demodulated signal so it can be heard or output to another device.

The receiver designs discussed below use audio as the output device. They assume that the operator will be listening to the demodulated and amplified received information. However, the same receivers can be used as part of a digital station, in which case, the AF subcarrier output from the receiver would be passed to a hardware or a software modem for digital decoding. This was covered in section 12.9 Digital Modes.

As mentioned on page 170, modern transmitters and receivers extensively use digital signal processing (DSP) for signal modulation and demodulation. However, the superheterodyne receiver, explained in this chapter, is still widely used in modern radios because it is a building block of a hybrid SDR receiver, even if it may be replaced with fully digital SDR one day.

Some of the components shown in this chapter, notably various detectors (demodulators) are unlikely to be found in modern transceivers which use DSP for demodulation purposes. However, knowing them is useful, and is required by the exam syllabus. If you plan on building a receiver on your own, you are likely to find one of these purely analogue designs to be a good starting point.

13.1 Superheterodyne Receiver

The most common analogue design of a receiver is the SUPERHETERODYNE, also called a SUPERHET. It can be used on its own, or as a building block of a hybrid SDR

receiver, see section 13.6.2. Figure 13-i shows its overall, simplified block diagram. All the components are explained in section 13.3 further.

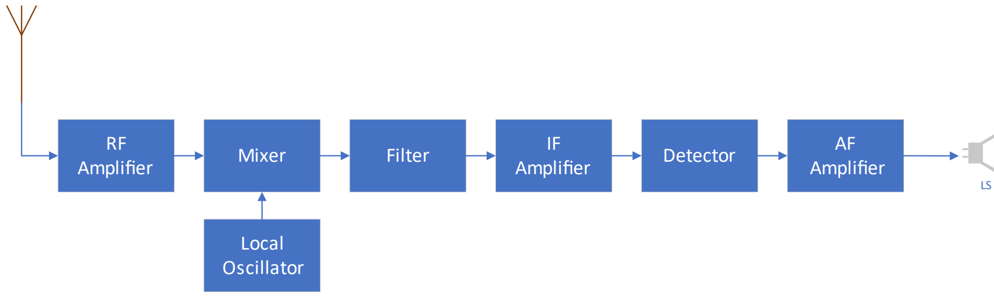


Figure 13-i: Superheterodyne receiver. [EI9ILB]

The operating principle of a superheterodyne relies on the mixing of signals. Just as with the mixers used in transmitters, when two signals mix, frequencies that are the sum and the difference of both original signals are created.

The incoming RF signal is converted to a fixed IF by the local oscillator and mixer. The frequency of the local oscillator must be carefully chosen and matched with appropriate filters for the superheterodyne to work. This is explained further below. The selectivity and the gain of the receiver are determined at this fixed IF.

13.2 Double Conversion Superheterodyne Receiver

The difference between a double conversion superheterodyne and a simple superheterodyne is that there are two IFs generated by two mixers. Figure 13-ii shows a simplified block diagram of a double conversion superhet.

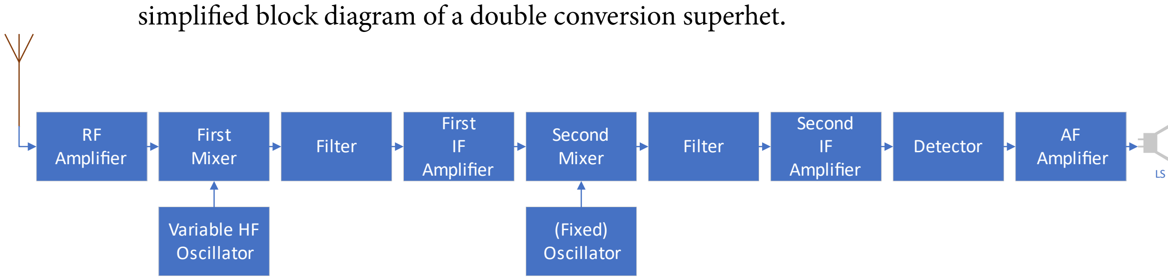


Figure 13-ii: Double conversion superheterodyne. [EI9ILB]

The incoming signal is first converted to a higher IF, for example, 10.7 MHz, or 1.6 MHz. It undergoes first filtering at that stage. Subsequently, it is converted to the final low IF, for example, 455 kHz, for further filtering and amplification.

This design is better at solving the problem of image rejection because the first filtering stage can operate at a higher IF than in the simpler design. At the same time, it can provide good adjacent channel selectivity, which is determined by the second stage of filtration. Image rejection is discussed in section 13.7.4.

13.3 Receiver Components

13.3.1 RF Amplifier

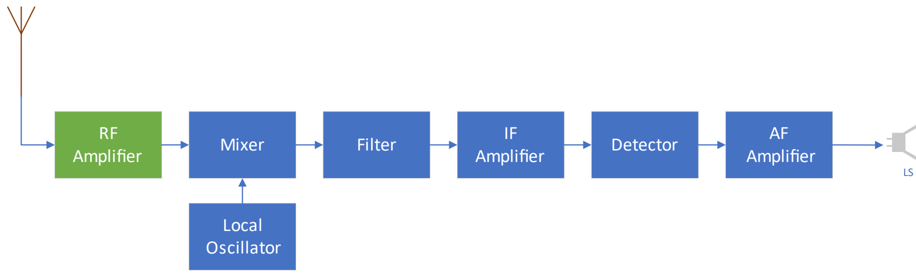


Figure 13-iii: Receiver: RF amplifier. [EI9ILB]

The RF AMPLIFIER increases the power of the weak RF signal received by the antenna so that the remaining electronic components can process it. Even though the amplified signal is now much stronger than the AC flowing from the antenna, it is still relatively low. For example, it would not be powerful enough yet to drive a speaker.

The design of the RF amplifier, related to its gain control, influences the receiver's selectivity. It should reject unwanted nearby signals on HF, or adjacent VHF or UHF channels. The RF amplifier should also have a low noise design, with a good signal to noise (SNR) ratio, to help achieve good receiver sensitivity, to hear even the quietest stations.

The RF amplifier usually has a manual RF GAIN control letting the operator control selectivity. Figure 13-iv shows an arrangement of gain controls, with the RF gain controlled by the outer, and the AF gain (see section 13.3.9) by the inner knobs. This gives the operator a fine level of control over receiver's selectivity, sensitivity, and volume.

Figure 13-iv: AF and RF gain controls. [EI6LA]

The AUTOMATIC GAIN CONTROL (AGC) and manually switched ATTENUATORS are often provided to prevent overload of the later processing stages by strong incoming RF signals. Such overload would cause distorted audio. In a digital receiver it could prevent the DSP from being able to demodulate the signals. SDR receivers have a red warning *overload* light that indicates when this situation arises.

13.3.2 Local Oscillator

The LOCAL OSCILLATOR produces a local signal at a frequency that is offset from the desired incoming RF signal by the IF. The local oscillator frequency depends on the frequency the operator wishes to tune to. As the operator turns the tuning knob, the frequency of the local oscillator changes.

The local oscillator may be constructed from a variable tuned circuit. In modern receivers it is digitally synthesised, often by DDS. See 6.4 DAC and Direct Digital Synthesis.

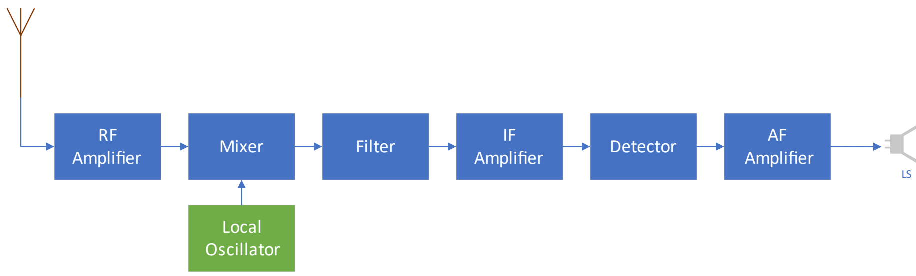


Figure 13-v: Receiver: local oscillator. [EI9ILB]

13.3.3 Mixer

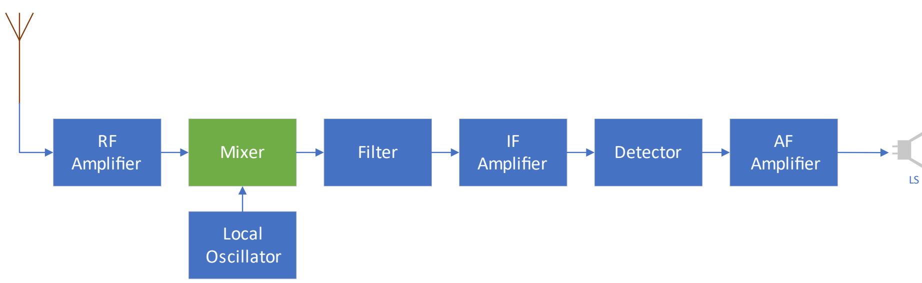


Figure 13-vi: Receiver: mixer. [EI9ILB]

The MIXER has two inputs. It combines the incoming amplified RF signal with the local oscillator signal to produce the low, fixed IF.

The fundamental principle of frequency mixing is that new frequencies are created: the sum of the two, and the difference between the larger and the smaller of the inputs. Their harmonics will also be created in this process. However, only one of those frequencies is necessary: the fixed IF. It will be selected by the filter.

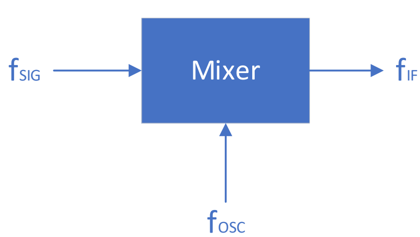


Figure 13-vii: Inputs and outputs of a mixer. [EI9ILB]

Focusing on the wanted IF, the effect of a mixer can be explained with a simple formula. f_{SIG} represents the frequencies in the input RF signal. The frequency of the

signal generated by the local oscillator is f_{OSC}, and f_{IF} stands for the desired, fixed IF, as shown in Figure 13-vii. To calculate the f_{IF} use this formula:

$$f_{IF} = | f_{OSC} - f_{SIG} |$$

The two vertical bars || that surround the difference (subtraction) of the incoming and the oscillator frequencies mean that the result of the subtraction should be always taken as a positive number. To achieve that, simply switch the two frequencies around so that the larger one comes first.[231] For example, if the incoming signal frequency is 7000 kHz, and the local oscillator is 7455 kHz, the IF would be 455 kHz.

$$f_{IF} = | 7455 - 7000 | = 455$$

Even though 455 kHz is the wanted IF, the mixer will also produce a frequency of 14455 kHz, being the sum of the incoming and oscillator signals, and also their harmonics, i.e., their multiples. Those will be easily removed by the filter.

13.3.4 IF Filter

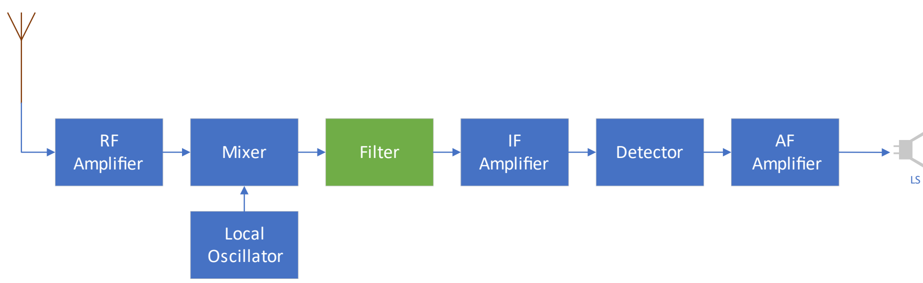


Figure 13-viii: Receiver: IF filter. [EI9ILB]

The IF FILTER fulfils two important functions. Firstly, it selects the IF, removing other frequencies, including the unwanted mixing by-products. Secondly, it removes all frequencies outside of the bandwidth of interest. It is usually a BAND-PASS FILTER. It also sometimes known as the ROOFING FILTER.

This is one of the most important filters in the receiver. It must be able to filter accurately even if there are strong, nearby signals, which are almost always present outside of the bandwidth of interest. Recall from 8.4.3 that digital filters have limitations and are not yet able to filter strong out-of-band signals. Even the most advanced digital receivers come with traditional, analogue, crystal, or ceramic filters, even if advanced filtering is also performed digitally, by the DSP.

For example, when listening to SSB phone, especially when the band is congested, perhaps during a contest, the operator wants to listen only to a narrow bandwidth, 1.8–2.4 kHz. Otherwise, having tuned to one signal, the operator would be hearing

231 Mathematically, the vertical bars stand for *absolute*. An absolute value, in this case, simply means a positive number. If you were to subtract the larger from the smaller, you would get a negative value. To get an absolute result you could also just drop the *minus* from in front of the negative result.

the nearby conversations on lower and higher frequencies.[232] Similarly, when receiving CW, the operator usually wishes to only hear one signal, and a narrower bandwidth of 100–500 Hz may be required. Otherwise, too many CW transmissions will be heard at the same time, making their decoding difficult.

On the other hand, with some digital modes, it may be useful to hear multiple transmissions simultaneously. For example, if the radio is receiving FT8, a relatively wide filter would be used, 2.7–3 kHz or more, so that the audio subcarrier being output to the attached computer, which is running the decoding software, can decode all the FT8 conversations currently taking place. The software modem performs its own digital filtering of each individual 50 Hz FT8 transmission from the wide set of all of them while decoding them all simultaneously.

The typical bandwidths of IF filters used in receivers are shown in Table 13-A. The exam syllabus does not require you to learn those filter bandwidths but knowing them will make it easier to relate the function of the filter to different modulation types and their bandwidths, which you are required to know. See Chapter 11 Modulation and Modes.

Table 13-A: Typical receiver IF filter bandwidths

Mode	Typical filter bandwidth
CW	100–500 Hz
SSB Phone	1.8–2.4 kHz
SSB Data	2.7–3 kHz
FM	12.5 kHz

Some receivers offer an option of installing additional filters, especially for CW and RTTY. The range of the preinstalled filters differs greatly, depending on the model and the price of the receiver. Fully digital receivers may come with only wider roofing filters, letting the DSP filter narrower bandwidths.

In addition to IF filtering, all modern receivers also offer another, final level of filtering of the processed audio, just before it reaches the speaker. By combining IF and AF filtering it is possible to listen to very weak signals in noisy and congested conditions.[233]

13.3.5 IF Amplifier

The process of mixing and filtering reduces the power of the signals, and they need to be strengthened for the next stage, the detector.

232 Those nearby conversations would sound unnatural, though, and they would be much higher or lower in pitch, on SSB. Regardless, they would be a nuisance.

233 If you have access to a receiver, you may want to experiment with the different filter settings. Tune to a station that is neither too clear nor too weak. Compare what happens when you engage different filters, especially if your receiver allows you to select different IF and AF filters.

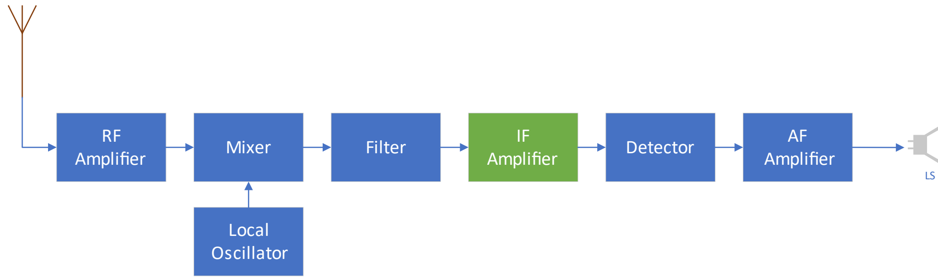


Figure 13-ix: Receiver: IF amplifier. [EI9ILB]

The IF AMPLIFIER, which follows the filter, operates at a fixed IF. Because of the fixed frequency, it is possible to maximise the gain and the selectivity of the IF stages compared to the RF input stages where a wide range of frequencies are present. This design also offers cleaner signals than a design with a stronger RF amplifier, because the signal that is now being amplified has already undergone some filtering.[234]

13.3.6 Detector (Demodulator)

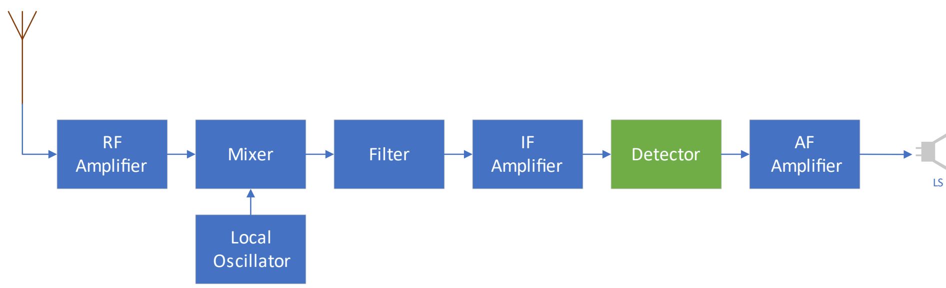


Figure 13-x: Receiver: detector (demodulator). [EI9ILB]

The DETECTOR, also known as the DEMODULATOR, recovers the original information: the underlying modulating signal from the received modulated signal. Different detectors are needed for different modulation modes.[235]

The simplest, purely analogue detector is a rectifying diode. Section 10.1 introduced it for the purpose of rectifying AC into DC. However, the diode has many other uses. A simple circuit consisting of a diode, a capacitor, and a resistor, can demodulate

234 If you have access to a receiver, tune it to a medium quality signal on a noisy band. Compare what happens if you use more RF gain and less IF or AF gain – AF gain is often just called *volume*. Then see the other way round. You should notice that in noisy conditions using less RF gain and compensating for that with IF or AF gain you will be able to hear the station just as well, or even a little better, but the noise should become much lower. Increasing RF gain will help the quietest stations as long as the noise levels are very low. Control over the receiver's amplification stages, RF, IF, and AF, is useful.

235 The name *detector* comes from the early days of radiotelegraphy, long before radio was used to transmit audio. In the late 19th century radio was used to transmit Morse code characters. The presence of radio signal indicated that the transmitter's key was down, and its absence meant it was up. The detector detected the presence or absence of the signal, and so, which part of the character was being transmitted: a dit, a dah, or a pause between them.

AM. If fed with AC containing the AM signal, it will recover from it the information that was impressed onto the carrier wave during modulation in the transmitter, such as the audio containing speech. The simplicity of AM demodulation is one of the reasons for its popularity during the twentieth century AM long-wave radio era.[236]

Nowadays, however, it is far more common to use a hybrid SDR design that uses DSP for all demodulation purposes, see section 13.6.

13.3.7 Product Detector (CW and SSB)

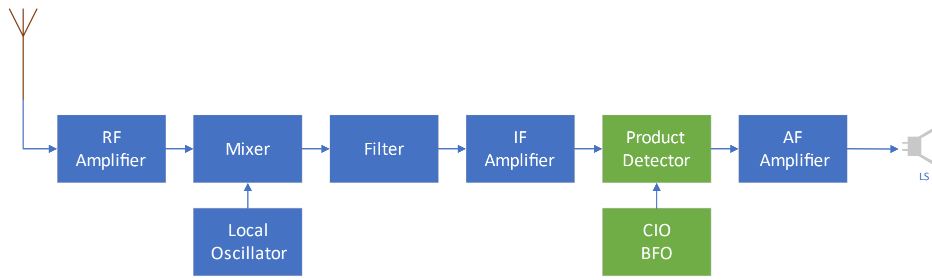


Figure 13-xi: Receiver: product detector used with CW and SSB. [EI9ILB]

The PRODUCT DETECTOR is a type of a detector, or demodulator, that works just like a frequency mixer. It mixes the modulated IF signal with a sine wave. The sine wave is generated using an oscillator. The oscillator has different names depending on the job it is doing. To demodulate SSB, it is called the CARRIER INSERTION OSCILLATOR, CIO, and its frequency is that of the IF, for example, 455 kHz.

To demodulate CW, it is called the BEAT FREQUENCY OSCILLATOR, BFO, and its frequency is slightly offset from that of the IF, for example by 800 Hz, i.e., 455.8 kHz in this example. That offset will cause an audible tone to be generated by the product detector at the AF of 800 Hz (a high pitch) when receiving a Morse character, while the transmitter's Morse key is down. It will remain silent in the pauses between the characters when the transmitter's key is up.

Modern transceivers demodulate CW, SSB, and other modulation schemes digitally using DSP. However, the simplicity of the above design means it is very straightforward to build a CW receiver from scratch.

13.3.8 FM Demodulator and Limiter

The demodulation of FM signals requires a special type of a detector. Two common types of FM DEMODULATORS are DISCRIMINATORS and PHASE LOCKED LOOP (PLL) detectors. There are other types. However, before FM signal is passed to one of those FM demodulators, any variations in its amplitude, such as those caused by noise or fading, need to be removed.

236 This type of a detector, or demodulator, is also known as *envelope detector*, as opposed to the product detector, discussed in the next subsection. See en.wikipedia.org/wiki/Envelope_detector.

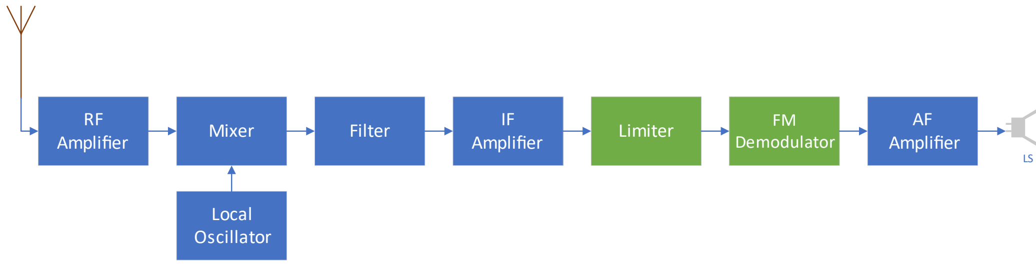


Figure 13-xii: Receiver: limiter and FM detector (demodulator). [EI9ILB]

The LIMITER ensures that the amplitude is steady, making the job of the demodulator easier.

13.3.9 AF Amplifier

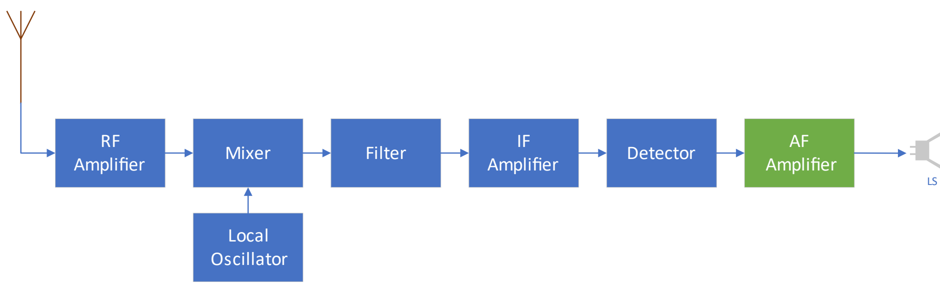


Figure 13-xiii: Receiver: AF amplifier. [EI9ILB]

The final stage of signal processing in a simple receiver is the AF AMPLIFIER, which is an AUDIO AMPLIFIER. The demodulated signal has low voltage and low current. Its power is so low that it would not be heard on a loudspeaker. The AF amplifier increases its power so that it can be heard.

The AF amplifier gain is adjustable by means of turning the *volume* control, which, on amateur radios, is often labelled as AF GAIN, in contrast to the RF gain.

Instead of a loudspeaker or headphones, the AF amplifier's output may be sent to an attached computer that is running a software modem in a digital station, see 12.9 Digital Modes. The audio subcarrier that has just been demodulated using SSB now contains digital information, such as FT8 or RTTY FSK signals, that still require further demodulation or decoding using the software modem. It is important to set the level of the AF gain so that together with any further amplification by the computer's sound interface the resulting audio level is not excessive for the software to be able to demodulate it without distortion.

13.3.10 Automatic Gain Control (AGC)

The AGC automatically adjusts the receiver's gain to maintain a constant output level. This assists the operator so that they do not need to constantly adjust the AF gain

(volume) even if the signal becomes much stronger or much weaker during a transmission. AGC also prevents the overload of the amplifier stages, which would lead to a distortion of the received signal.

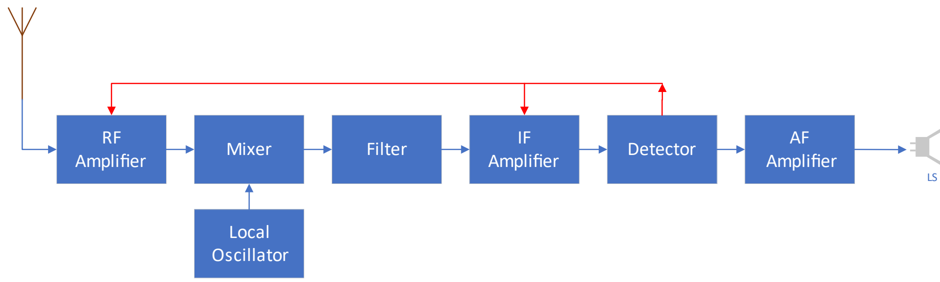


Figure 13-xiv: Receiver: automatic gain control, AGC. [EI9ILB]

The AGC is particularly useful when listening during congested conditions where many stations, with different signal strengths, transmit one after another, for example, a quieter CW station followed by a very loud one. AGC ensures that the RF or IF gain is proportionately reduced when the detector demodulates the loud signal. When the loud station stops, AGC readjusts the RF and IF gain so that the quieter one can be heard clearly. Modern receivers allow a choice of faster and slower AGC reaction times. Some operators prefer the slower reaction when receiving speech, and faster with CW. Additionally, many receivers use the AGC circuit to drive the S METER.

13.3.11 S Meter

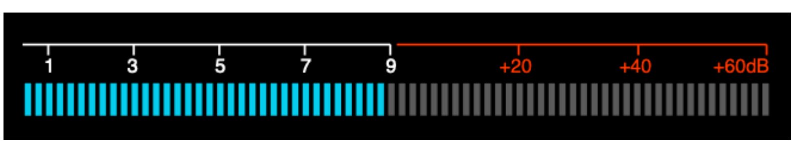


Figure 13-xv: Digital S meter showing an S reading of just under 9 S points. [EI6LA]

The S METER indicates the strength of the received signals. It is usually measured at the output of the IF stage or the detector. It has a scale showing S POINTS from 0 to 9. Above S9 the S meter shows signal strength in dB above the level associated with S9. These readings are shared when giving the RS or RST signal report, see section 29.5. There is an IARU standard that sets the meaning of S meter values in terms of signal rms voltage at the receiver's input terminal, assuming 50 Ω impedance.[237]

- S9 represents 50 µV (microvolts) on HF
- S9 represents 5 µV on VHF

237 The agreement over the value of S9 was established in the early 20th century. The later IARU R1 Technical Recommendation R.1 was issued in 1981. See en.wikipedia.org/wiki/S_meter.

Each one S unit corresponds to a 6 dB difference in power, i.e., quadrupling of power. Recall that +3 dB means doubling of power, and -3 dB means halving the power, see Chapter 9 Power Ratios and Decibels.

Unfortunately, even though there is broad agreement about the meaning of S9, the implementation of this standard is not universal, with some commercial receiver manufacturers using their own scales. Some modern receivers have an option to switch to the common IARU standard.

13.3.12 Squelch

The SQUELCH is an operator convenience feature primarily used in FM receivers. It suppresses audio output in the absence of a sufficiently strong input signal. It prevents noise from being heard. The setting of the squelch threshold control knob determines how strong the received signal must be for the audio output to open. Any signals below the selected threshold will not be output, and, instead, there is silence. If the setting is too high, potentially weak but audible signals will not be heard at all.

13.4 SSB and CW Receiver

A simplified but complete, purely analogue SSB and CW receiver, including the AGC and the S meter is shown in Figure 13-xvi. Please refer to the earlier sections in this chapter for explanations of its components.

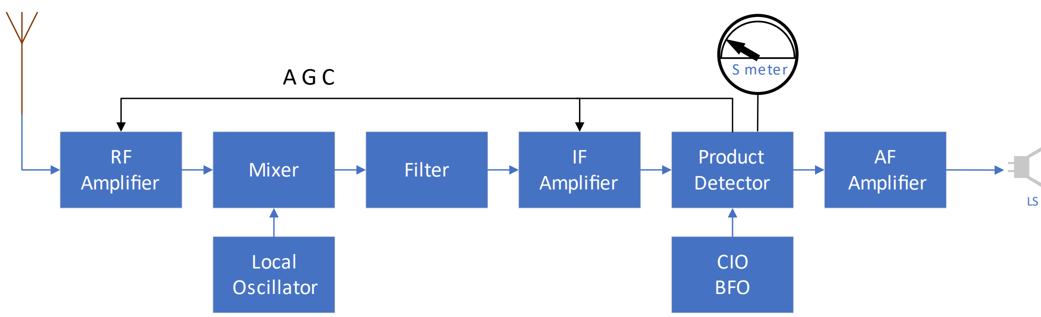


Figure 13-xvi: Complete SSB and CW receiver. [EI9ILB]

13.5 FM Receiver

A simplified, complete, purely analogue FM receiver is shown in Figure 13-xvii. Bear in mind the location of the S meter, which is different from the SSB and CW receivers.

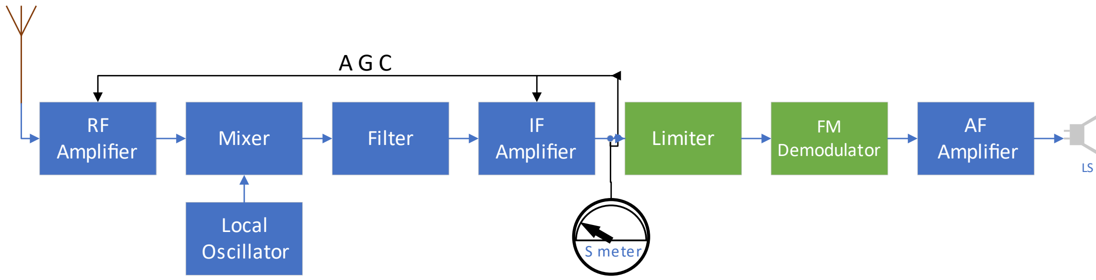


Figure 13-xvii: Complete FM receiver. [EI9ILB]

13.6 Modern Receivers and SDR

As mentioned in the introduction to this and the previous chapters, modern, commercially sold transceivers use digital signal processing (DSP) for signal modulation and demodulation purposes. The hybrid SDR design, which combines DSP with the analogue, superheterodyne receiver is very popular. However, the most recent, fully digital direct sampling designs are slowly replacing the hybrid approach.

The fundamentals of DSP have been discussed in Chapter 6. Make sure to review the explanation how the basic DSP and SDR components work, in particular, the analogue-digital converter, ADC, in section 6.3, the digital-analogue converter, DAC, as well as direct digital synthesis, DDS, in section 6.4, and the difference between hybrid and fully digital designs, section 6.5.2.

13.6.1 Fully Digital Direct Sampling SDR Receiver

Figure 13-xviii shows a simplified block diagram of a fully digital, DIRECT SAMPLING SDR receiver. You will find this design in almost all the recent, commercially available transceivers.[238] As these are still early days of fully digital SDR transceivers, the details of commercial implementations vary greatly, and not all manufacturers are forthcoming with the details of their designs. Unfortunately, unlike analogue radios, which anyone can study by analysing their physical components, SDR, which relies on proprietary software, tends to be more of an opaque design, unless documented.

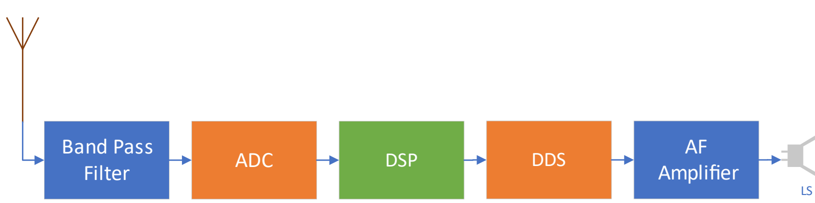


Figure 13-xviii: Direct sampling SDR receiver. [EI9ILB]

238 Including Apache, Elecraft K4, Flex Radio, ICOM IC-705, IC-7300, IC-7610, and YAESU FT-710.

Current SDR and DSP technologies have limitations. With regards to receivers, a key limitation concerns the band-pass filter, which is the very first filter in the signal processing chain.[239] Strong out-of-band signals would have a profoundly detrimental effect on the DSP, either making its intended job impossible, or by increasing the noise level and introducing loud unwanted artefacts.

Software filters are not yet able to remove strong out-of-band signals, see section 8.4.3 Digital Filters. Except for very basic, simplistic SDR modules, all modern SDR-based receivers rely on traditional, electronic circuits for incoming signal filtering.[240] Even if using inexpensive USB SDR sticks, it is necessary to equip them with a set of traditional filters.

The ADC works at the RF in the direct sampling design. It must offer a high enough resolution for good SNR and a high dynamic range, see 6.3.3 Sampling Rate and Resolution.

A direct sampling ADC must sample the incoming RF at a frequency that is at least twice the highest frequency of the signal, see 6.3.4 Minimum Sampling Rate. ADCs working at HF need to sample at least at 60 MHz, which is possible nowadays. However, to directly sample the 2 m band 144 MHz VHF signal, the ADC, and the remaining digital chain, must operate at least at 288 MHz. Such ADCs are complex, expensive, and they are not yet available in commercial amateur VHF receivers.[241] For those reasons, additional digital circuitry can be employed within an ADC to perform a frequency down-conversion to reduce the required sampling rate for a more economical design.

The ADC converts the RF AC into digital data, which is a sequence of numbers, representing the received, modulated signal. The digital representation is either at the RF, or, more commonly, at a lower IF.[242] Some ADCs produce so-called baseband signal, which is still modulated, although at zero Hz frequency.

The DSP performs several functions in an SDR receiver. Most importantly, the DSP is responsible for all signal demodulation tasks, replacing the need for traditional detectors discussed earlier. Modern receivers can also decode some digital signals, such as RTTY FSK, PSK, and even some CW.

Modern receivers also use aspects of the DSP to display a waterfall spectrogram (frequency domain plot) of an entire band, see 6.5.1 SDR as a Broadband Receiver. The DSP also performs extensive signal improvements, notably advanced digital filtering, and noise reduction. It allows the operator to apply audio enhancements, such as bass/treble adjustment, to the demodulated audio.

Since the output from the DSP is digital data, it must be converted back to AF AC before it can be played on a loudspeaker. DDS (or another technology) can perform this conversion. This is like how streamed or downloaded digital music becomes audio in a music player. The final processing stage involves audio amplification. The

239 The band-pass filter may be preceded with an RF amplifier in some direct sampling designs.
240 ICOM IC-7300 has over fifteen analogue band-pass filters for this purpose.
241 ICOM IC-9700 ADCs cannot sample VHF at the necessary frequency. See footnote 89 on page 68.
242 Because this IF is digital, rather than AC, it is sometimes called *pseudo IF*.

function of the AF amplifier is no different from the purely analogue designs discussed earlier.

13.6.2 Hybrid SDR Receiver

The HYBRID SDR receiver design is still a common design in commercially sold transceivers, even though the fully digital direct sampling seems to be outgrowing it in popularity.[243] This design combines the most successful analogue receiver design, the superheterodyne, with the DSP working at a lower IF. There are many advantages of this design, notably, the well-understood analogue circuitry is good for preconditioning the RF signal before its further digital processing.

The block diagram of the hybrid SDR receiver, shown in Figure 13-xix, uses a simple superheterodyne, see section 13.1. The superheterodyne, represented by all the components preceding the ADC, works in the same way as in a traditional, analogue receiver. It delivers the IF signal to the digital stages. The ADC converts the AC IF to its digital representation, so that it can be processed by the DSP. The purpose and the function of the DSP, and of the remaining components, DDS and the AF amplifier, is identical to the fully digital direct sampling receiver, discussed in the previous section.

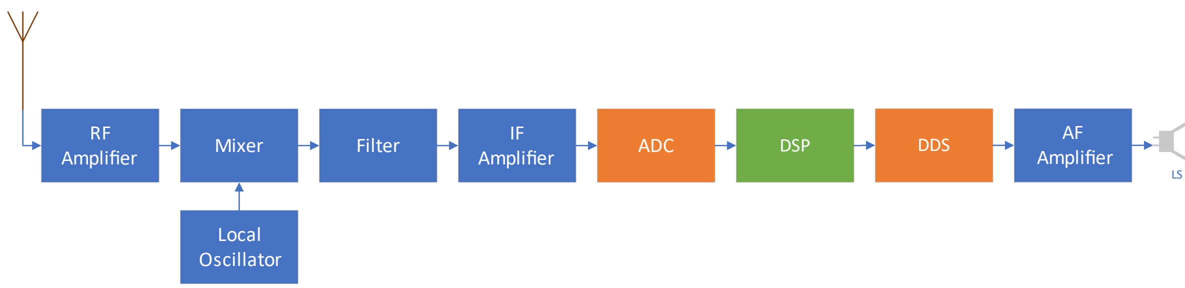


Figure 13-xix: Hybrid superheterodyne SDR receiver. [EI9ILB]

A notable difference between the hybrid and the direct sampling designs is that the IF produced by the superheterodyne can be a much lower frequency than in a purely analogue receiver.[244] Achieving such a low IF is easier with a double, or even a triple conversion superheterodyne.

By using a low IF, the ADC and the DSP can operate at low sampling rates. This is advantageous for many reasons. Notably, it allows the ADC to have a high resolution, yielding good SNR, a good dynamic range, and a low latency (no delayed audio), whilst being more economical than direct sampling RF ADCs.

243 Including Elecraft K3, Kenwood TS-890S, Yaesu FTDX-10, FTDX-101/MP.

244 Hybrid SDR IF is usually 12–192 kHz, with a popular choice is 24 and 36 kHz because there are many commercial ADC and DSP integrated circuits that operate at 24 and 36 kHz. They are used in music players, digital TVs, and mobile phones, because those frequencies are close AF. However, Yaesu FTDX-10 and FTDX-101/MP directly sample superheterodyne output at 9 MHz IF.

13.7 Receiver Characteristics

The quality of the received and processed signal depends on the design of the receiver. The most important characteristics are discussed in this section. Maximising them all would be complex and expensive. Knowing these characteristics will make it easier to find an economical receiver that has the qualities that are important to you.

13.7.1 Sensitivity and Signal-to-Noise Ratio (SNR)

The SENSITIVITY is the ability of a receiver to resolve weak signals satisfactorily without introducing noise. It means that you can hear even the quietest stations.

Recall that RF signal coming from the antenna is AC. Considering that the nominal impedance of the receiver is known, the voltage of that AC represents the amplitude, and so the power of the signal.[245]

Sensitivity is defined by stating the minimum signal voltage at the input to produce an output with a certain ratio of SNR in a specified bandwidth at a particular frequency. Recall that SNR, being a power ratio, is measured in dB. Sensitivity is usually measured in µV (microvolts) with a minimum 10 dB SNR. The lower the value of sensitivity the better, because it means that less powerful signals can still produce adequate output.

For example, a traditional receiver may require 0.5 µV to produce 10 dB SNR in 3 kHz bandwidth at 28 MHz frequency. A more recent receiver will have a better sensitivity, requiring only 0.16 µV to achieve the same results. To benefit from such exceedingly high sensitivity, one needs almost noise-free radio conditions.[246]

13.7.2 Selectivity and Adjacent Channel Characteristics

The SELECTIVITY of a receiver is its ability to separate the required signal from unwanted or interfering ones, especially if they are very close, as frequently happens in congested MF and HF band segments. On channelised VHF and UHF good selectivity is easier, as it only needs to reject signals in nearby channels.

Using good quality, narrow band-pass filters, with sharp transition bands, increases selectivity and can reduce interference. The usable passband is determined by the mode being used. Using filters narrower than the passband may help in some cases, however, it usually increases the overall noise level and can cause audible artefacts, such as ringing.

245 The reason that the current does not need to be considered stems from Ohm's law. Since the nominal impedance is fixed at 50 Ω, knowing just voltage is enough to know the power of the signal, i.e., its strength. See also 3.10.2 Power and Ohm's Law.

246 Manufacturers publish their own figures the specifications. Magazines and web sites publish their own tests. A respected, independent source is Sherwood Engineering, see sherweng.com/table.html.

13.7.3 Dynamic Range

The DYNAMIC RANGE of a receiver is the range of signal levels over which it can operate. It is the range of the quietest to the strongest RF signals that it can process.

The low end of the range is governed by the sensitivity of the receiver. The high end of the range is governed by its overload (overdrive) limits or its strong signal handling performance. If the receiver is overdriven, it will become non-linear and it will produce significant distortion. This is a similar problem to an overdriven transmitter, except it only affects the receiving station.

The dynamic range is expressed as the ratio of the strongest to the weakest signal the receiver can handle. Like many ratios, it is expressed in dB. Typically, the dynamic range is as high as 90–110 dB.

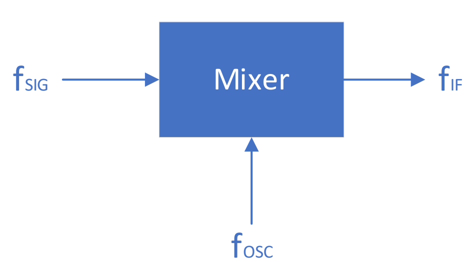
Recall that in a digital, SDR receiver, the dynamic range, just as the SNR, are directly related to the resolution of the ADC, see 6.3.3 Sampling Rate and Resolution. Modern, SDR-based transceivers display an *overload* warning when the dynamic range has been exceeded. An attenuator can be engaged to resolve the issue, albeit at a price of a loss of some receiver sensitivity.

13.7.4 Image Frequency and Image Rejection

In a superheterodyne, the mixer, see 13.3.3, will produce an output at the IF for more than just the single frequency of interest. The mixer always produces frequencies that are separated from the frequency of the oscillator by the same distance, on either side of the oscillator's frequency.

For example, if the frequency of the oscillator, f_{OSC} is 7455 kHz, the desired intermediate frequency, f_{IF} of 455 kHz will be produced by the mixer from two signals: the desirable one selected by the operator at f_{SIG} of 7000 kHz but also from an undesirable f_{SIG} of 7910 kHz. Figure 13-xx shows the effect of mixing those frequencies.

$$| f_{SIG} - f_{OSC} | = f_{IF}$$



$$| 7000 - 7455 | = 455 \text{ kHz}$$

$$| 7910 - 7455 | = 455 \text{ kHz}$$

Figure 13-xx: Image frequency. [EI9ILB]

Recall from section 13.3.3 that the vertical bars | | indicate an absolute result, i.e., a positive number even if the result of the subtraction were to be negative. In this example, $7000 - 7455 = -455$, however, the absolute of -455 is 455. Because $7910 - 7455$ is also 455, that means two entirely different transmissions would end up being mixed into the same IF. That second frequency of the unwanted transmission is known as the IMAGE FREQUENCY.

IMAGE REJECTION, i.e., the removal of the image frequencies before they reach the mixer, requires a filter just before the mixing stage. That filter removes all unwanted transmissions that could potentially fall into the range that is too close to the frequency of the oscillator feeding the mixer. To do that, however, a relatively high IF is necessary.[247] Unfortunately, using a large IF introduces another problem: it reduces the selectivity of the receiver, reducing its ability to separate adjacent signals, because of the difficulty of building suitably narrow yet high-frequency filters.

A double conversion superheterodyne solves those problems. It uses a high first IF to allow for image rejection, and a low second IF to provide good selectivity. An example of first and second IF is shown in Figure 13-xxi.

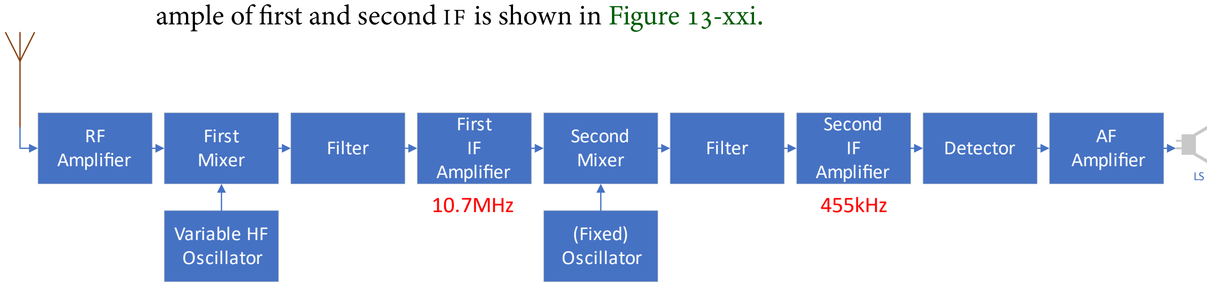


Figure 13-xxi: High first IF of 10.7 MHz for image rejection and a lower second IF of 455 kHz for selectivity in a double conversion superheterodyne. [EI9ILB]

As the name suggests, a triple conversion superheterodyne would employ a third IF, which is helpful when converting to an even lower IF used by hybrid SDR designs.

13.7.5 Noise Figure and Factor

A NOISE FIGURE, or a noise factor, is the degradation in SNR as the signal passes through an amplifier or the entire receiver. It is an important characteristic in VHF and UHF, but less so at the lower frequencies.

13.7.6 Stability

The ability of a receiver to remain tuned to a particular frequency is determined by its STABILITY. It is the receiver's equivalent of the transmitter frequency stability characteristic, see 12.5. Unlike in a transmitter, it only affects the receiving station.

247 With the exception of narrow band receivers. To design a receiver that operates on a wide band, a low IF would require many switched or variable filters. It is simpler to use a high enough IF.

Stability depends on the electrical and mechanical stability of tuned circuits, particularly oscillators, and is affected by the heat generated during operation. Modern, SDR-based receivers have excellent stability. Amongst the analogue designs, solid state receivers are more stable than their valve-based predecessors.

13.7.7 Desensitisation and Blocking

Strong signals that are relatively close to the wanted signal may cause DESENSITISATION (SSB) or BLOCKING (CW) of early signal processing stages in a receiver. It is caused by an overdriven internal amplifier of the receiver, which reduces its overall response to weak signals. It manifests as a temporary reduction in the receiver sensitivity. A weak station near a strong signal cannot be heard, even if the strong signal itself is not being listened to. Sensitivity returns to normal when tuning further away from a strong nearby signal. This problem may be also caused by other local, and therefore very strong, amateur stations. Very strong stations outside of the IF passband can also cause it. The ability to cope with such strong nearby signals without desensitisation or blocking is an important characteristic of a receiver.

13.7.8 Intermodulation

IMD is covered in section 18.2, where its harmful form is discussed from the perspective of a transmitter. While IMD is not harmful to other spectrum users in a receiver, it can significantly reduce the quality of the received signals, and it can even prevent their successful reception or decoding. It is caused by the unavoidable by-products of mixing of different frequencies. While those by-products are normally quiet and do not affect the reception, an overdriven amplifier inside a receiver, just like in a transmitter, can cause them to be amplified more than the wanted signal. It results in distorted audio.

If the amplifier operates within its range, IMD increases the receiver's NOISE FLOOR, which adds a low-level of noise that reduces the receiver's SNR and sensitivity.

13.7.9 Cross-modulation

CROSS-MODULATION is a transfer of modulation from a stronger, undesirable signal to a weaker, wanted one. It is related to intermodulation, but it has a different mechanism. Non-linearity of any component in a receiver may cause that component to act as a modulator, causing unwanted mixing of otherwise unrelated signals.

For example, an overdriven amplifier, or another component which is operated outside of its normal range, such as a filter, can cause the modulation of one signal to be imparted on another signal. There can be other causes of cross-modulation in a receiver. The AGC system may cause gain to vary in proportion to the amplitude of the interfering signal. As a result, modulation of the strong unwanted signal will be impressed on the wanted, weaker signal. It is desirable for receivers to resist cross-modulation.

14 Transmission Lines

FOUR EXAM QUESTIONS · SECTION A6

TRANSMISSION LINES are an essential component of every radio station. Their job is to pass RF signals between the devices, and between the equipment located inside and outside of a radio station. They are also known as FEEDERS, FEEDER LINES, or FEEDLINES. You may think of them as simply CABLES. However, because they operate at RF they need to be chosen and used carefully to make the transfer of RF power as efficient as possible. Several types of transmission lines, including coaxial cables, open wire parallel lines, and waveguides, are discussed in this chapter.

In addition to physical characteristics, such as ease of handling and durability, the main properties of a transmission line are its characteristic impedance, line loss, and the velocity factor.

14.1 Characteristic Impedance

Every transmission line has a CHARACTERISTIC IMPEDANCE, denoted using dimension symbol Z_0. Like all impedance, its unit is ohm, Ω. A commonly used characteristic impedance is $50\ \Omega$, found in such coaxial cables as the popular RG-58. The characteristic impedance of an ideal transmission line is purely resistive, i.e., it has no reactance, see 8.3 Reactance, Resonance, and Impedance.

Characteristic impedance is determined by the physical design of the line, especially by the type and the size of the conductors, the spacing between them, the dielectric that separates or surround the conductors, and the overall construction. See also 8.2.1 Dielectrics.

Characteristic impedance does not depend on the length of line: it is the same no matter how long or short is the piece.[248]

14.2 Line Loss (Attenuation)

An ideal transmission line of any characteristic impedance, including $Z_0 = 50\ \Omega$, would be lossless, delivering 100% of the power to the antenna, no matter its length. Real transmission lines are not ideal, and they can cause considerable losses to the power being transmitted through them.

The LINE LOSS is the attenuation, or the loss of power travelling in a transmission line. Power is lost (dissipated) to heat in the line because of the resistance of the conductors, and the heating of the dielectric that absorbs some of the RF energy. Both types of losses depend on the length of the line. They both depend on frequency, but dielectric losses only become significant at UHF and above.

248 This may sound confusing because the *resistive losses* of a conductor depend on its length. However, characteristic impedance, ideally purely resistive, does not describe those losses. Losses are characterised by *line loss,* a different property of a transmission line.

Line loss is the ratio of RF power delivered to the antenna and the power supplied to the line. Like all power ratios, line loss can be expressed in decibels, see 9.2 Power Ratios. Line loss is measured in dB per unit of length, usually dB per 100 metres, or dB/m, for a given transmission line. Line loss increases with the frequency. High quality cables are necessary for VHF and UHF to avoid significant losses.

Some types of transmission lines have very low loss. For example, open wire transmission line, discussed in 14.5 Parallel Lines, can have loss as low as 0.5 dB per 100 m at 28 MHz. Others, like coaxial cables, especially with a small diameter, have considerably higher losses, like 7 dB per 100 m of RG-58 at 28 MHz.[249]

Resistive power losses[250] depend on the resistance and the AC current travelling through the line. The higher the current, the greater the power dissipated as heat in a given line. Dielectric losses of power depend on the frequency and the voltage in the line. Since power, voltage, and current, are related to each other, transmission lines have a POWER RATING or a MAXIMUM VOLTAGE RATING which should not be routinely exceeded. Otherwise, the line, especially its dielectric, can melt, or cause arcing, resulting in a short and damage to the transmitter or an amplifier.

There are two other factors causing losses of power in a transmission line: standing waves and feedline radiation. Standing waves increase both the current and the voltage on the line, and the associated resistive and dielectric losses. They are discussed in 14.9.2 Unmatched Case and Standing Waves.

Feedline radiation is another form of a loss that can occur if the transmission line is not used appropriately, some examples are given in 14.4 Preventing Line Radiation.

14.3 Velocity Factor

Electromagnetic waves travel in free space (vacuum) at the speed of light, see 7.1 Radio Waves and Electromagnetic Radiation. They travel almost as fast in the air. However, they travel at a lower velocity in transmission lines. Depending on the construction of the line, especially the amount of solid material present within its cross-section, waves travel at between 65% and 95% of the speed of light.[251]

249 Recall that a loss of 3 dB means halving of the power. A loss of 7 dB on a 100 m coaxial line would mean that less than a quarter of the power would reach the antenna. If transmitting 100 W, only about 20 W would be delivered, while 80 W would be lost to heat in the line. A lower loss coaxial line would be RG-213, losing just over 3 dB, half of the power. If a long run was necessary, there are even better but also more expensive coaxial lines, or a low-loss open wire feeder could be considered.

250 Also known as *ohmic losses*.

251 The way electric current travels through a *conductor* is interesting. For example, in a 2 mm diameter bare copper wire connected to a 1 A source of DC, electrons move extremely slowly, only about 1 mm per minute, a speed known as *drift velocity.* The reason electric current appears to travel so much faster than that, at 95-99% of the speed of light, is because when an electron moves, even slowly, it causes an electromagnetic wave to propagate along the cable's wire, which is acting like a *wave guide*. That wave, in turn, induces a current, which moves the remaining electrons along the length of the conductor, which reinforce the wave, which moves the electrons, and so on. This interaction of the wave with the electrons in the conductor slows down the wave to a little less than the speed of light. In a transmission line, unlike in a bare copper conductor, the electromagnetic wave is further slowed down by its interaction with the dielectric.

The fraction of the speed of light at which an electromagnetic wave travels in a transmission line is known as the VELOCITY FACTOR, K. It is a number between 0 and 1. For example, the velocity factor of an open wire transmission line is approx. 0.85–0.9, meaning that a wave travels at 85–90% of the speed of light in an open wire. Commonly used, flexible coaxial cables that use polyethylene dielectric, are much slower, with a velocity factor of about 0.66, which means that an electromagnetic wave travels at 66% of the speed of light in them. There are less common, rigid types of low loss coaxial cables that have much higher velocity factors.

14.3.1 Electrical Length of a Line

Velocity factor makes it possible to calculate the ELECTRICAL LENGTH of any wire in terms of the wavelength of a frequency of interest. By knowing if a piece of a transmission line is a full electrical wavelength of some frequency, or a half wave, or a quarter wave, enables it to be used to solve various antenna impedance mismatch problems and to build filters.[252] Just by adding or removing a known length of a transmission line some antennas can be made to perform better.

For example, an approximate full wavelength of 14 MHz frequency in free space can be calculated using the formula shown in 5.1.3 Wavelength and Frequency.

$$\lambda = \frac{300}{f} = \frac{300}{14} = 21.4\ \mathrm{m}$$

Half-wavelength in free space of this frequency would be half of that.

$$\frac{21.4\ \mathrm{m}}{2} = 10.7\ \mathrm{m}$$

To calculate the electrical length, multiply the free space wavelength by the velocity factor.

$$\text{electrical length} = \lambda K$$

In our example, electrical half-wavelength of 14 MHz in a coaxial line whose velocity factor K is 0.66 would be, approximately:

$$10.7\ \mathrm{m}\ \times\ 0.66 = 7.1\ \mathrm{m}$$

A length of about 7.1 m of this coaxial transmission line would be electrically as long as the 10.7 m that is the free space half-wavelength of 14 MHz.

14.4 Preventing Line Radiation

Radiation from the transmission line, also known as FEEDLINE RADIATION, or LINE RADIATION, is undesirable. It radiates some of the power in ways that are not optimal for radio communication purposes and leaves less power to be transmitted

252 Simple but effective filters can be built from precise lengths of transmission lines by leaving one end open or shorted. They are known as *stubs*.

from the antenna. It can cause issues and interference by bringing RF into the radio room or to sensitive objects near the transmission line.

For example, using a single, bare wire as a transmission line would not work well, because it would act as an antenna. AC travelling in such a conductor would create an EMF around it, and it would radiate energy all along its length.

Transmission lines are designed to prevent line radiation. The three common designs are parallel lines, coaxial lines, and waveguides. They work differently to achieve the same goal: confine all the power within the transmission line and deliver all of it to the attached load, usually the antenna. They must be used correctly. For example, a parallel line that is severely bent, or touching a grounded metal conductor, will not function properly.

14.5 Parallel Lines

PARALLEL LINES, historically also known as BALANCED LINES, are usually constructed from two parallel conductors, separated from each other by spacers or flat, ribbon-like insulation. The two conductors are kept at a precise, identical distance from each other all along the length of the line. There may be openings, also known as windows, in the insulation. Parallel lines of this type go by many names: OPEN WIRE, PARALLEL CONDUCTOR LINE, LADDER LINE, WINDOW LINE, TWIN LEAD, or TWIN FEEDER. Their operating principle is simple. The two *parallel* conductors are intended to carry identical (balanced) currents travelling in opposite directions. If this can be achieved, the EMFs created by each conductor cancel each other out, preventing feedline radiation.[253] This is illustrated in Figure 14-i.

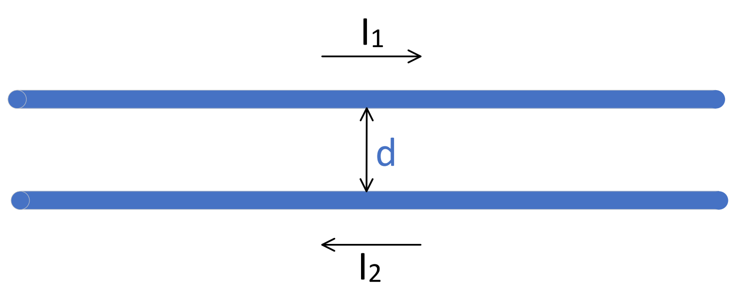


Figure 14-i: Parallel line. Identical AC currents, $I1$ and $I2$, travelling in opposite directions through conductors separated by a distance d. [EI9ILB]

Examples of popular parallel lines are shown in Figure 14-ii and Figure 14-iii.

253 If the currents in both conductors of a parallel line are equal-and-opposite, the electromagnetic far fields of each conductor are identical, but 180° out of phase with each other. When they superimpose, they cancel out and no feedline radiation occurs.

Figure 14-ii: Open wire transmission line, also known as ladder line or parallel line. Two conductors separated with insulating spacers, approximately 50–150 mm apart. [EI9ILB]

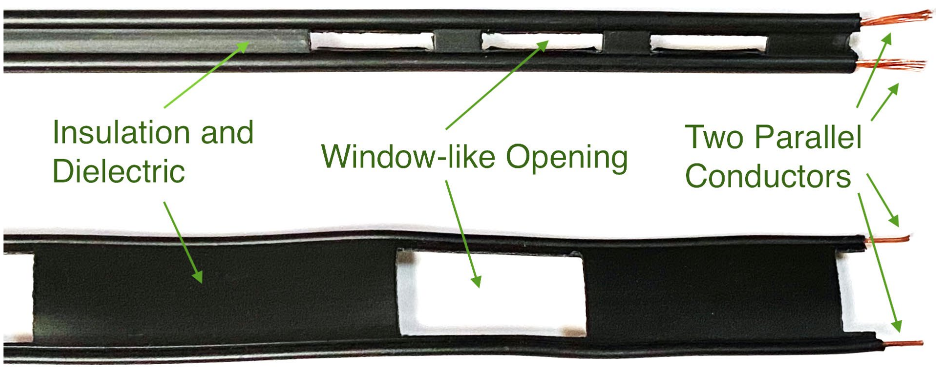


Figure 14-iii: Window lines, 300 Ω (top) and 450 Ω (bottom). Top uses a stranded copper-clad steel wire, bottom uses solid copper wire. Solid copper wire is more prone to breakage in wind. [EI6LA]

The characteristic impedance and the velocity factor of parallel lines depends on the diameter of the conductors, distance between them, and the type of the dielectric that separates them. In case of parallel lines, both the air and the insulating material act as a dielectric.[254] Line loss of a parallel line depends on the diameter of the conductor. The properties of typical parallel lines are:

- Characteristic impedances: 600, 450, 300, and 75 Ω
- Velocity factor: 0.85–0.95
- Line loss, if not *wet:* 0.3–0.5 dB/100 m at 28 MHz

Parallel line must be kept away from any other metallic objects, away from the ground, and it should not be bent excessively. Otherwise, the EMFs would no longer cancel each other fully, causing some feedline radiation. It should also be away from

254 The insulating ribbon provides the rigidity and ease of handling. The size and the number of the windows influences the mutual capacitance between the two conductors, determining the characteristic impedance. The openings reduce the effect of rainwater. Water changes the characteristic impedance because it has a different *dielectric constant* than plastics or the air. It is not desirable for a transmission line behaviour to vary depending on the weather.

other parallel lines, and other nearby sources of RF EMFs. Otherwise, the signals from those sources may interfere with the one carried in the parallel line. RF sources that are further away usually do not affect parallel lines.

Because the parallel line depends on the currents being identical in both conductors it can become unbalanced if those currents become uneven. Contrary to an older belief that parallel lines are *self-balancing,* unbalance can occur easily in real-life environments. This often happens when feeding a dipole antenna that, itself, becomes unbalanced due to the proximity of metallic objects, wire fences, buildings etc. This can cause common mode currents and feedline radiation. These consequences can be mitigated, to some extent, by use of chokes, see 14.8 Common Mode Current and 14.11 Baluns and Chokes.

14.6 Coaxial Line

COAXIAL LINES are very popular because they are so convenient to use. They are commonly referred to as COAXIAL CABLE, COAX CABLE, or simply as COAX.[255] Unlike parallel lines, coaxial lines are very tolerant about their environment. They are flexible, they can be twisted and bent, they can be placed next to other cables, on the ground, over it and even underground, next to metallic objects, and they are easily attached using common connectors. Their versatility makes them the most popular type of transmission line used in radio applications. The name coaxial means *concentric:* the conductors, dielectric, and the insulation, all form circles, whose centre is the centre conductor.

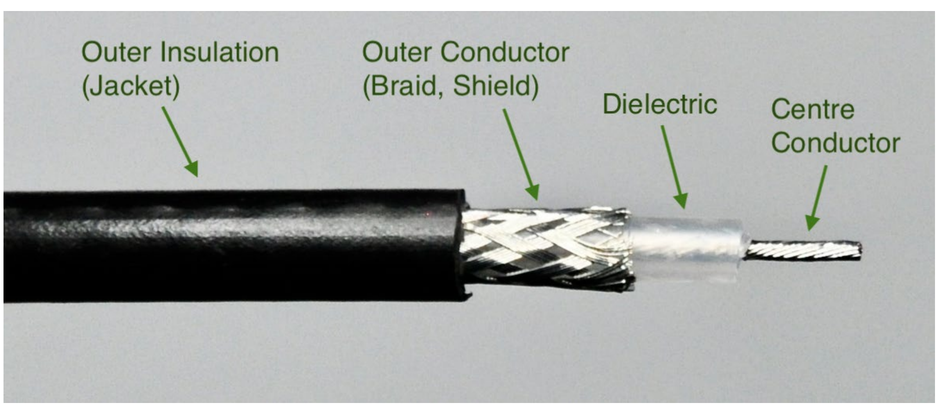


Figure 14-iv: Coaxial cable construction, single-shielded. [EI9ILB]

255 Coaxial cables were used as transatlantic undersea telegraph cables, first in 1858, from Valentia Island in Ireland to Bay of Bulls, Trinity Bay, Newfoundland, now Canada. Their function was improved when their theory was explained by an English physicist and mathematician, Oliver Heaviside, who also patented them, in 1880. He is responsible for much radio theory, including the key to transmission lines known as the *telegrapher's equations,* and the current form of the foundation of classic electromagnetism, *Maxwell equations,* which he rewrote.

At first sight, Figure 14-iv, shows that the coaxial cable has two conductors: the CENTRE CONDUCTOR, and a surrounding tubular OUTER CONDUCTOR or SHIELD, usually made from braider copper wire for flexibility, also known as the BRAID. They are separated with a DIELECTRIC, such as PVC, Teflon, or foam. The very outside of the outer conductor is physically protected by a tough, flexible plastic outer insulation cover, or JACKET. This is vital to protect the cable against water ingress, because even a small amount of water would irreversibly damage the shielding braid. More complex designs may have additional shields.

The above interpretation of a shielded coaxial cable is correct at DC and very low frequencies, but at higher radio frequencies the picture changes significantly.

At HF and above, RF currents only flow over the surface skin of conducting materials, with no significant penetration through their thickness. The interior and exterior of the coax shield will then behave as two separate conductors. This means that, at RF, a coaxial cable effectively has a total of *three* conductors rather than two. The outside skin of the centre conductor carries the wanted RF signal current, with its return current flowing exclusively on the inside skin of the shield.[256]

Because the inside surface of the shield completely surrounds the centre conductor, strong electromagnetic coupling ensures that these two currents are exactly equal-and-opposite. Nothing escapes through the shield, so the interior of a coaxial cable is completely protected from the outside world. That is what makes coaxial cable so tolerant of its external environment. Because the interior of the cable cannot interact with the outside world, it is not a direct source of feedline radiation, unless experiencing problematic common mode currents on the outside of the shield.

The outside of the shield acts as a separate conductor which interacts with the outside world. It behaves like an additional, thick, single wire. The current flowing on the surface skin of the outside of the shield is known as common mode current. It allows the outside of a coaxial cable to act as a single-wire antenna, unexpectedly radiating and picking up unwanted signals that may not even be on the same frequency as the signal inside the cable. Suppression of these unwanted common-mode currents is necessary. Common mode chokes can be used for this purpose. They are discussed in section 14.8.

The inside and the outside surfaces of the coaxial cable shield can only interact where they meet at an open end. Special attention must be paid to the way that coaxial cables are connected.

Because coaxial cables work on a different principle from the parallel lines, historically known as balanced lines, they are often classified as UNBALANCED.[257]

The two most common coaxial cables used in HF applications both have the same characteristic impedance 50 Ω and velocity factor 0.66. They are:

256 This is *skin effect*. The conductor acts as a waveguide, with little current flowing within. The higher the frequency, the shallower the depth. See gm3sek.com/2020/07/26/the-private-life-of-coaxial-cable.

257 The historical balanced vs. unbalanced classification is neither intuitive nor helpful. Each type of line has its own advantages and disadvantages, but neither is automatically better than the other.

- RG-58: a very flexible cable with a 5 mm outside diameter, and a rather high line loss, with lower maximum power rating. It is commonly used indoors to make connections between equipment and for shorter runs to an antenna.
- RG-213: a stiffer cable with a 10.3 mm outside diameter, a lower line loss than RG-58, and the ability to carry higher levels of power.[258] It is mainly used outdoors and for longer runs towards antennas.

14.6.1 Coaxial Connectors

When planning what coaxial cables to use, consideration must also be given to the type of coaxial connectors that terminate them. The most popular design is the UHF connector. The name UHF is historical, as those connectors are primarily used in HF applications. UHF connectors often carry old US military designations, PL-259 male plug and a SO-239 female socket. Cables usually have male plugs on both ends and equipment has the sockets.

A wide variety of PL-259 and SO-239 connectors exist. Some can be crimped, some are soldered, and some use compression fittings. It is important to match the connector to the diameter and the design of the chosen cable. Figure 14-v shows a few common examples.

Figure 14-v: UHF connectors. PL-259 compression fitting (left), SO-239 to PL-259 right angle (centre), PL-259 crimp fitting with soldered centre pin (right). [EI6LA]

The quality of the chosen connector, and the way it has been attached to it, can significantly affect the performance of a coaxial transmission line.

14.7 Waveguide

Commonly used WAVEGUIDES carry RF signals by letting the electromagnetic wave reflect from its inner walls.

258 Line loss of RG-58 vs RG-213 at 28 MHz is 7 dB/100 m vs. 3.5 dB/100 m at 28 MHz. At 14 MHz the line loss is, respectively, 4.5 dB/100 m and 2.4 dB/100 m. There are coaxial cables with lower losses and better flexibility, but more expensive, such as Messi & Paoloni. Very low loss coaxial cables exist that are almost completely stiff, known as *hard line*. Cables with soft PVC jackets cannot be buried under ground but can be buried in conduits, while other have a stronger jacket and may be designated for *direct burial*. Others seem flexible, but should not be bent tightly, because of fragile, foam-based dielectrics. Some withstand heat better. Some can carry high levels of power.

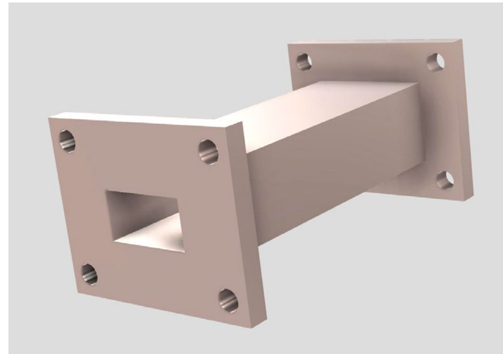


Figure 14-vi: Waveguide segment. Typical outside dimension of a 10 GHz waveguide would be about 25 × 12 mm, a bit larger than coaxial cables. [EI9ILB]

Waveguide is like a tube, circular or rectangular, and it comes in straight and various elbow sections which can be joined together to form a long transmission line, see Figure 14-vi. It is used at the higher end of UHF and above.

Coaxial cable can be also thought of as a type of a waveguide. However, as the frequency of the signal increases, especially over 2 GHz, large coaxial cables no longer function correctly due to internal resonances, while losses in smaller coaxial cables become unacceptable, unlike in a waveguide.

! Never look into an active waveguide to avoid serious injury. Eyes are particularly sensitive to a range of frequencies used in UHF applications.[259]

14.8 Common Mode Current

The RF signal is carried inside a coaxial cable between the inner side of the outer conductor and the centre conductor, see 14.6. Current flows on the surface of centre conductor, and on the inner surface of the outer conductor. The outside of the outer conductor picks up and carries currents which can become a nuisance. They are generally referred to as COMMON MODE CURRENTS. They are not unique to coaxial cables. They will flow in a parallel transmission line if the currents in the conductors are out of balance with each other. This can happen if the parallel line is connected to an antenna, such as a dipole, that becomes unbalanced due to the proximity of metal objects. The two conductors of a parallel line will also act as a receiving antenna and pick up currents from any nearby transmissions. It can also happen if the parallel line lies at an angle that is not perpendicular to the antenna it is connected to. In that case the parallel line will be closer to one side of the antenna than the other, and it will pick up the signal being transmitted from it. In all those cases, common mode currents will add to the intended currents already flowing in the transmission line, causing issues.[260]

259 Some of those frequencies are close to the frequencies used by microwave ovens, such as 2.45 GHz. WI-FI uses a similar frequency, 2.4 GHz. While ovens may use 1 kW of power or more, the power of the dispersed WI-FI signal is very low and well within safety guidelines. The focused energy in an active waveguide may be much higher and dangerous, especially to the head and eyes.

260 The desirable currents in a transmission line are known as *differential mode* currents because they consist of two currents, travelling in opposite directions. They travel in the two parallel line conductors, or inside a coax, one on the surface of the centre conductor, and the other on the inner surface of the outer conductor. The common mode current shares direction with one of those currents, and adds to it, hence the name, *common*.

In a coaxial cable, the outside of the outer conductor (shield) receives nearby EMF which induce the common mode currents to flow on its surface. The major source of those fields can be the transmitting antenna itself. However, other EMF will be also picked up. Unless they are dealt with, common mode currents will join with the signal current at cable's ends, usually at places where it is connected to equipment or to an earthing point. Common mode current can also transfer between coaxial and parallel lines.

If the coax cable outer conductor is properly connected to a good earth, those currents should dissipate to ground and not cause issues.[261] This technique may be used in combination with common mode chokes to block the flow of common mode currents. Without such precautions, common mode currents will add to the signal and interfere with it, increasing noise.[262] If they are strong enough, common mode currents can also reach troublesome levels indoors, and radiate close to equipment, causing equipment issues, such as malfunction of computer devices. They can even cause milder but still unpleasant RF burns when touching poorly grounded metallic objects, such as microphones or Morse keys, see 19.3.2 RF Burns from Direct and Near Contact with RF Currents.

While good RF earth can dissipate common mode currents, they can be also greatly reduced by using common mode chokes, as noted above and in 14.11.

In summary, avoid common mode currents by designing the antenna and the transmission line so that all the elements that are intended to carry balanced RF currents do remain in balance, employ suitable chokes, and provide good RF earth, if possible, to coaxial cable's outer conductor.

14.9 Impedance Matching and Transformation

For the maximum transfer of power from the source (transmitter) to the load (antenna) the nominal output impedance of the transmitter should match the characteristic impedance of the transmission line, which should also match the feed point impedance of the antenna. The characteristic impedance of the transmission line should match the impedance of anything connected to it to allow for the maximum amount of undistorted power to be delivered without losses.[263] If there is no

261 A good earth, in this context, means more than the essential *protective earth* provided by the properly bonded electrical installation of the building. In addition to providing the essential safety, which can never be compromised on, good earth should be also able to dissipate RF AC. This is harder to achieve than the dissipation of mains electricity AC, because it requires a path of sufficiently low impedance to earth at the higher, radio frequencies. This is a complex area and may not be achievable or even desirable in many installations. In those cases, the use of suitable common mode chokes is a better option. See also 19.4.2 Protective Earth, including footnotes 352, 354, and 355.

262 Arguably, the common mode current received from the transmitting antenna's field should not affect the reception, because the transmitting station is not listening at that moment. However, it can affect connected equipment, cause RF burns, and impair the antenna's receiving performance. Common mode current on transmit is also a reliable sign that the feedline picks up local interference on receive. With multiple stations at a field day or in a contest station, this problem becomes complex.

263 Power amplifiers are designed to present some mismatch between their actual output impedance and the nominal, expected impedance of the load, to improve efficiency. See 12.3 Output Impedance.

match, some of the power will reflect back-and-forth between the source and the load. Those reflections will cause further losses in the line, and, if excessive, damage the equipment and the line. Small amounts of reflections are unlikely to be an issue.

14.9.1 Matched Case

A transmission line terminated with a load (usually an antenna) that is purely resistive, i.e., that has no reactance, and whose impedance is equal to the characteristic impedance Z_0 of the transmission line is said to be MATCHED. This is an ideal case of perfect impedance matching. Figure 14-vii shows a schematic of a match.

Figure 14-vii: Impedance matching: matched case. Transmitter (AC source, generator) on the left. Resistor, on the right, represents the load, such as the antenna. Transmission line is represented by the two conductors in the middle. [EI9ILB]

In a matched case, the transmission line appears to the source as an infinitely long line. All of the RF power is absorbed or radiated by the resistive load, and none is reflected back towards the source. This is the most desirable situation. The voltage of the AC on a matched transmission line is equal at every point of the line, as shown in Figure 14-viii. The same applies to the current. There are no standing waves of voltage or current in a matched case.

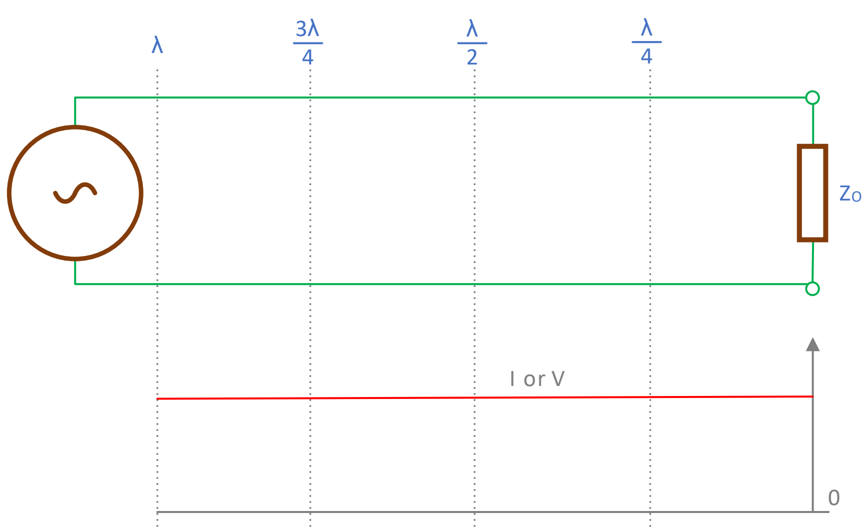


Figure 14-viii: Voltage V or current I along a matched transmission line. [EI9ILB]

14.9.2 Unmatched Case and Standing Waves

A line terminated by a load whose impedance is different than the characteristic impedance of the transmission line is said to be UNMATCHED, as schematically shown in Figure 14-ix.

Figure 14-ix: Impedance matching: unmatched case. The load, on the right, has impedance that is not equal to the characteristic impedance of the transmission line. [EI9ILB]

With an unmatched load the impedance at the input to the transmission line differs from the characteristic impedance and the load impedance. Whenever there is such a mismatch, not all of the available power will be accepted by the load. Instead, some of the power reaching the load will be reflected back towards the source. It is known as REFLECTED POWER. Once the reflected power reaches the source, it will re-reflect back towards the load, adding itself to the power being generated by the source. This FORWARD POWER, which is the sum of the source's power and the re-reflected power, will appear to be higher on a meter than the power of the source!

For example, a 100 W source feeding a transmission line that is reflecting 20 W of power because of a mismatch will show forward power of 120 W.

The second time the forward wave travels towards the load, some of it will be absorbed or radiated, but a portion of it will be reflected once again towards the source. Fortunately, those reflections do not continue forever. Each time some of the re-reflected power is absorbed or radiated by the load. Eventually, all of the reflecting power is absorbed or radiated, except for line losses.

It is a common misconception that all the reflected power is somehow lost. It is not. All the power is eventually used by the load, except for some potentially significant line losses, explained in the next section.

Using our example, the NET POWER reaching the load is still 100 W, because the 20 W of reflected power was compensated for by its re-reflection from the source, which added to and increased the forward power to 120 W. The difference between the forward and the reflected power, the net power, is $120\ \text{W} - 20\ \text{W} = 100\ \text{W}$.

This explanation assumes that the source could re-reflect the reflected wave fully without absorbing any of it. The source absorbs a small amount of the re-reflected power causing an additional build-up of heat. Further, because the source is not seeing the impedance it was designed for, it is operating with a lower efficiency. Modern solid-state transmitters and amplifiers may not be able to do that with impunity. Too much reflected power can affect their longevity and, if excessive, cause damage.

14.9.3 Standing Waves on a Transmission Line and Line Loss

When the signal is reflected from an impedance-mismatched load its frequency does not change, but its phase changes. The voltage of the forward wave is out-of-phase with the voltage of the reflected wave. The same applies to the current. An out-of-phase voltage of the forward and the reflected waves will add or subtract in different places along the transmission line causing STANDING WAVES of voltage, and current, to form as shown in Figure 14-x.[264]

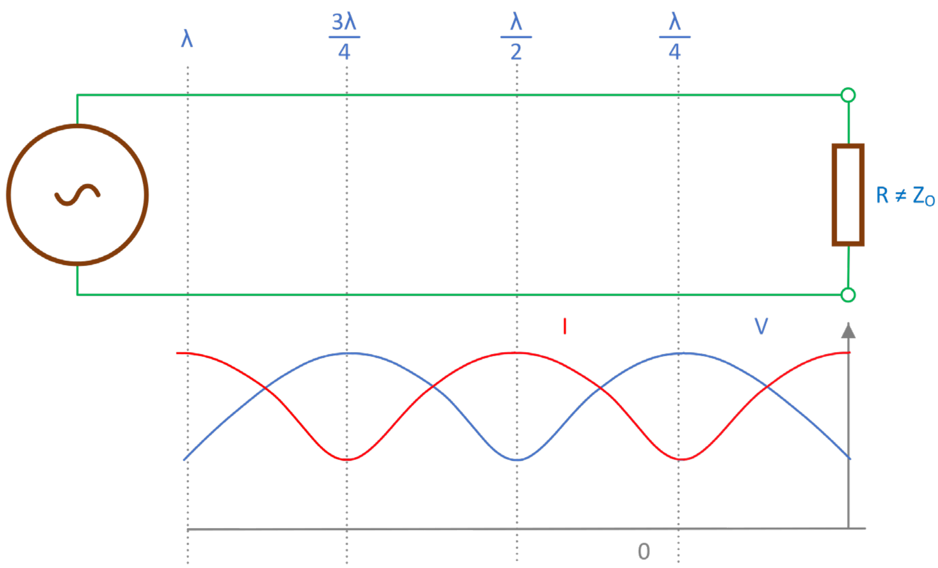


Figure 14-x: Sum of the voltage *V* (blue) and sum of the current *I* (red) of the forward and reflected signals (not shown). They form standing waves on a mismatched line. The nodes (minima and maxima) of the standing wave are at even fractions of the signal wavelength: at the end of the line, and at the ¼, ½, ¾, and 1 wavelength, and multiples, from the end, where the reflections start. [EI9ILB]

The standing waves, on their own, are not necessarily a problem. However, because they cause an increase of current, they lead to considerably higher resistive losses on the line.[265] The standing waves of increased voltage will, in turn, lead to higher dielectric losses. Power lost in both of those ways will dissipate as heat in the line. If the mismatch is sufficiently high, it can cause the excessive heat to damage the line.

These losses depend on the inherent line loss of the chosen transmission line. Because coaxial lines have higher line loss, they are more affected by high levels of reflected power, causing correspondingly higher losses. Parallel lines, which are

264 en.wikipedia.org/wiki/Standing_wave and commons.wikimedia.org/wiki/File:Standing_wave_2.gif

265 Voltage-related dielectric losses are smaller than the current-related resistive losses. The difference between the dielectric and resistive losses is a reason why they are uneven along the transmission line and tend to be higher at peaks of the current standing wave. This is also a reason why short transmission lines, less than ½ wavelength, may show a lower line loss when the load is slightly mismatched, when presenting a slightly higher load impedance than for a perfect match.

inherently low loss, and more effectively air-cooled, are less affected by reflected power. They are more suited towards applications where impedance matching is difficult.

Small amounts of mismatch are unlikely to cause any problems. Indeed, they may be practical, and might even help resolve other issues.

14.9.4 Standing Wave Ratio (VSWR)

A common way to express the level of reflected power is the VOLTAGE STANDING WAVE RATIO (VSWR) commonly referred to as STANDING WAVE RATIO, or simply SWR. It is the ratio of the highest voltage of a standing wave on the line to its lowest voltage.[266]

In a matched case, where the voltage is the same all along the line, with no standing waves, the ratio is 1/1 or, as it is commonly expressed, 1:1, or simply SWR of 1.

If the maximum voltage of a standing wave is twice as high as the lowest voltage on that line, the ratio would be 2/1 or 2:1, commonly referred to as SWR of 2. Some solid-state transmitters and amplifiers may not be able to work at their full power with this level of VSWR, but valve-based devices may still be able to function well.

If the voltage ratio is something in between, for example, 1.5/1 or 1.5:1, or simply an SWR of 1.5, modern electronics should cope, and the line losses should be still insignificant, especially when using shorter or higher quality transmission lines.

Transmission line losses caused by a high SWR depend on the inherent line loss of the line in question. In general, the SWR-related line losses are unlikely to be significant unless the SWR is exceptionally high.[267] Inherently low-loss parallel lines tolerate very high SWR with little loss.[268] SWR in itself is not an issue if you can accept the somewhat increased line losses. Even with a relatively high SWR the power produced by the transmitter is radiated by a mismatched line and the antenna. However, you should be aware of the SWR limitations of your equipment to prevent its premature heat or voltage-induced damage.[269]

It is common to use an SWR meter to monitor VSWR as well as the level of forward and reflected power. Section 17.2 shows an example of a popular type of an SWR meters and explains how to use it.

266 To find the highest and the lowest voltage, *absolute* voltages are considered, i.e., positive values even if the voltage is negative. For example, if the observed voltages on the line are +10 V, −5 V, and −7 V, their absolute values are 10 V, 5 V, and 7 V. The ratio will be calculated as 10/5 rather than 10/7. This is because the absolute value of -5, which is 5, is lower than the absolute value of -7, which is 7, even though -7 is lower than -5. Essentially, the formula is: $VSWR = |V_{max}| / |V_{min}|$

267 For example, RG-58 has line loss of 4.5 dB/100 m at 14 MHz with SWR of 1:1, i.e., a perfect impedance match. With a mismatch causing SWR of 1.5:1, the line loss will increase by only 0.2 dB, to a total of 4.7 dB/100 m. Even with SWR of 2:1, this line's loss will only increase by 0.5 dB, to a total of 5 dB/100 m, at 14 Mhz. It would require a rather high SWR of 6:1 to cause a 3 dB/100 m loss on this line, i.e., a loss that would cause half of the power to be lost to heat instead. A transmission line loss calculator is available at kv5r.com/ham-radio/coax-loss-calculator.

268 A 100 m long 450 Ω parallel line, such as the window line shown in Figure 14-iii on page 210 would require SWR over 25:1 to cause a 3 dB loss.

269 See *Understanding SWR by Example* www.arrl.org/files/file/Technology/tis/info/pdf/q1106037.pdf.

14.10 Antenna Tuning Units

An ATU, can be used to provide a match if an antenna's feed point impedance does not match the transmission line and the output of a transmitter. ATUs are also known as an ANTENNA MATCHING UNITS. It is used to match or transform the impedance presented by the antenna, or, by the combination of the antenna and the transmission line, to the to the nominal load impedance with which the transmitter or amplifier was designed to operate, normally 50 Ω. Although its main function is to improve the transfer of power, an ATU will also improve signal reception. ATUs are popular with multi-band antennas which usually present a variety of feed point impedances. They are rarely used with single-band antennas.

The best possible place for an ATU is right at the antenna's feed point, between the antenna and the transmission line, rather than between the transmitter and the line. The reason for that is that the ATU can present 50 Ω impedance to the transmission line, avoiding standing waves on the line, and therefore, without increasing line losses, which could be considerable, especially when using longer coaxial lines with multi-band antennas. To do that, a remotely operated ATU, or an automatic, remote ATU, may be necessary. However, if the unmatched SWR is not excessive, or the line losses are not considerable, for example, when the transmission line is parallel or short, the location of the ATU is less important.

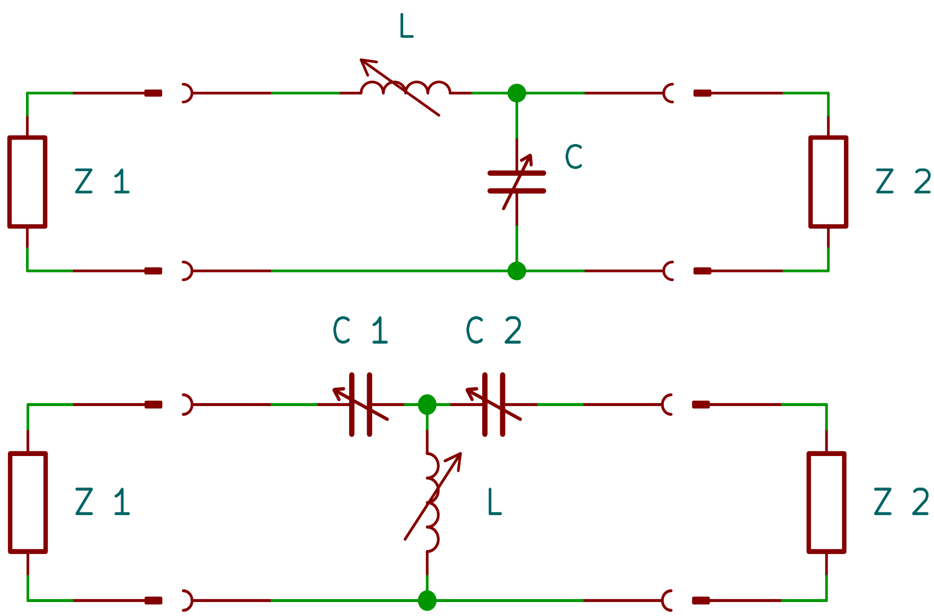


Figure 14-xi: Common ATU designs: L-match (top) and T-match (bottom). Z1 and Z2 represent two different impedances that need to be matched to each other. Z1 could be the transmitter, and Z2 the transmission line, or Z1 the line, and Z2 the antenna, depending on ATU location. [EI9ILB]

An ATU comprises variable (tuneable) inductors (coils), or a set of switched coils L and variable capacitors C to provide a choice of impedance matches. Those

adjustable components are shown using symbols with an arrow over them in the schematics in Figure 14-xi.

14.11 Baluns and Chokes

Half-wave dipoles and Yagis, discussed in the next chapter, are examples of antennas where the active element consists of two wires. Each of those wires needs to be connected to a transmission line at the antenna's feed point, which has two terminals, ready for a parallel line. The terminals have the same impedance. In use, the voltage, and the current in each wire of the antenna, and in the parallel transmission line would be equal-and-opposite, or, to use the historical term, balanced.

The more convenient coaxial cable is different. As explained in section 14.6, coax centre conductor, and the *inside* of the outer conductor, carry the valuable signal. When connecting the coax to the antenna's two terminals, a special device ensures that the signal on the inside of the outer conductor is kept separate from the common mode currents travelling on the outside.

A BALUN, which can be thought of as a *balancing* unit, is connected at the feed point of such an antenna.[270] It connects two antenna terminals on its one side to the coax on the other side. Directly connecting the coax to that antenna without a balun is not advisable. Signals travelling on the inside and on the outside of the *outer* conductor would be inadvertently mixed. Unwanted feedline radiation from the outside of the coax would become likely, and the radiation pattern of the antenna would also be impaired.

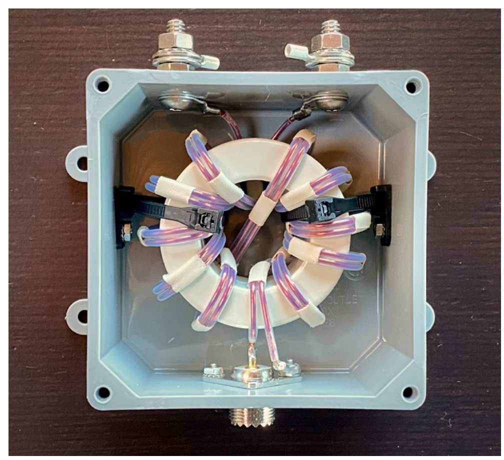


Figure 14-xii: Balun. 1:1 Current balun with a ferrite core. Coaxial input at the bottom. Balanced output at the top. [EI6LA]

Alternatively, an ATU designed for balanced antennas can be used with the coax, also helping match their impedances. However, a balun can be also designed to provide a fixed value of impedance transformation, to achieve an impedance match between the otherwise mismatched devices. It is known as a TRANSFORMER BALUN when used that way. It can sometimes replace the role of an ATU.

Additionally, to help avoid common mode currents travelling on the outside of the outer conductor of a coaxial cable, the outer conductor may be connected to a good RF earth. Unfortunately, that measure alone is not a replacement for the normally necessary balun and it may be ineffective because of the difficulty of providing a sufficiently good RF earth.

270 Historically, coax was called unbalanced, and parallel line balanced. Antennas such as dipoles also used to be called balanced. Balun stood for balanced to unbalanced matching device.

14.11.1 Voltage vs. Current Baluns

There are two common balun designs: voltage baluns and current baluns. A VOLTAGE BALUN is one whose output voltages, but not necessarily currents, are made equal and opposite. They are easily constructed and commonly used in spite of many limitations. A CURRENT BALUN is one whose output currents are made equal and opposite.

14.11.2 1:1 Current Balun and Common Mode Choke

Baluns usually take coax input but may differ in their output connectors. Figure 14-xii shows a 1:1 CURRENT BALUN with two output terminals (posts) at the top, and a coaxial input socket the at the bottom. It is used for antennas that have two feed point terminals. As the 1:1 in its name suggests, this balun does not change (transform) the impedance of the connected load. It is particularly useful if the antenna's impedance is already a good match for the line and the transmitter. A key ability of the 1:1 current balun is the suppression of common mode currents from entering or leaving the antenna. When used for that purpose it is also known as a COMMON MODE CHOKE, or simply, a CHOKE. 1:1 is the simplest of current baluns. A plain coil of wire, sometimes called an air-cored coil as shown in Figure 14-xv on the next page, can be an effective common mode choke but the useful bandwidth will be very narrow. To cover more than one amateur band, it will be more effective to use a ferrite core, like like the balun shown in Figure 14-xii on the previous page. The toroidal (ring-like) ferrite core is commonly known as a TOROID.

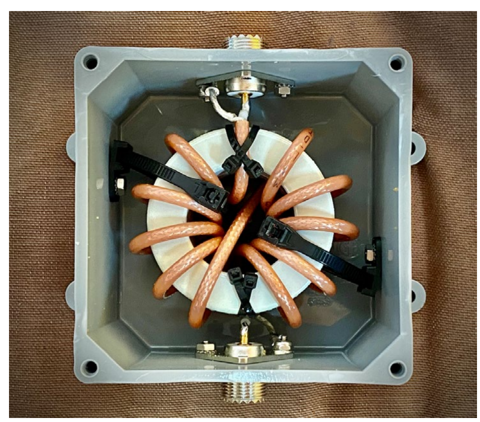


Figure 14-xiii: Common mode choke. Coax input at the bottom and coax output at the top. Design based on a feedline wound over a ferrite core (toroid). [EI6LA]

Baluns used as chokes on transmission lines can have both a coaxial output as well as a coax input. Figure 14-xiii shows such a choke. Ferrite core (toroid) chokes like the one shown in this figure can be a particularly effective way of suppressing common mode currents for installations that may have no access to a good RF earth.

The design of the balun, and the materials used, should be chosen based on the frequencies and the voltages it needs to serve, which depend on power, the SWR they must transform or withstand, and on the level of common mode currents it should suppress. Figure 14-xiv shows a different design of a choke, using ferrite beads over the coaxial cable. The larger the number of toroidal ferrite beads over the coax the more effective it can be at dissipating common mode currents.

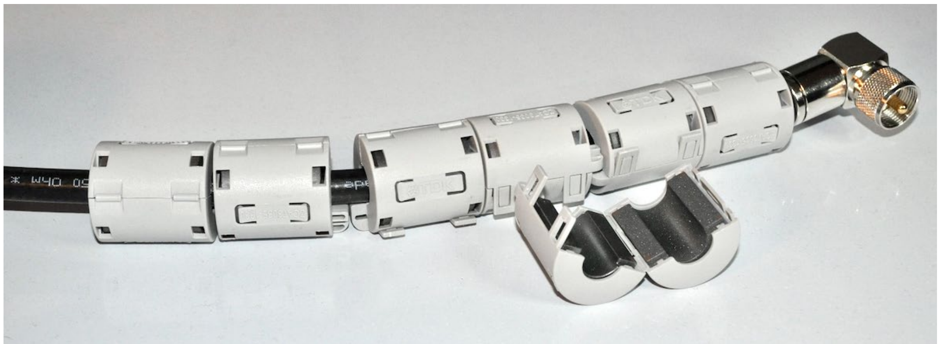


Figure 14-xiv: Common mode choke. Ferrite beads over coax, known as Maxwell balun. [EI9ILB]

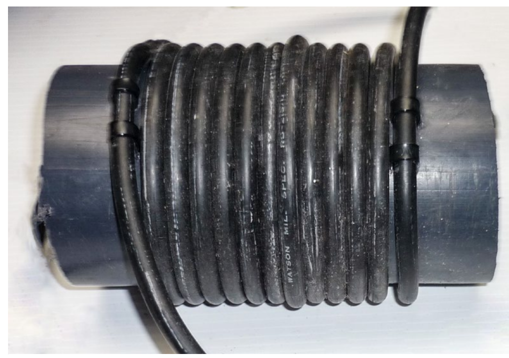


Figure 14-xv: Ugly balun. A common mode choke design using coax cable wound over an 11 cm diameter plastic pipe. [EI7ALB]

One of the simplest choke designs, also known as the UGLY BALUN, consists of several turns of a coaxial line coiled at the feed point of the antenna. Because of the coiling of the coax, the outside of the outer conductor becomes an inductor. Recall from section 8.1 that inductance presents an opposition to higher frequency AC. Since common mode current is RF AC flowing on the outside of the outer conductor, this simple design will inhibit its flow, essentially providing some isolation of the antenna from the remainder of the feed line that may be picking up common mode currents.

14.11.3 Voltage Baluns and Ununs

VOLTAGE BALUNS are designed like transformers, see section 10.5. They have a different number of turns of a conductor on either winding, usually using a dust iron or a ferrite core. As explained in Table 10-A on page 128 the impedance transformation ratio depends on the ratio of the turns of the winding.

Devices normally classified as voltage baluns provide 1:1 and 4:1 impedance transformation. When used as baluns, voltage baluns are inferior to current baluns because they do not provide common mode suppression.

UNUNS are a different group of devices. They are impedance transformers whose input and output connections are both unbalanced. Ununs with an impedance transformation of 49:1 may be used to match EFHW antennas, see section 15.10. This arrangement generally requires an ATU.

15 Antennas

FOUR EXAM QUESTIONS · SECTION A6

ANTENNAS, also known as AERIALS, and sometimes as RADIATORS, are the most important component of any radio station. This chapter introduces the principles of their operation while giving examples of a few popular designs. To make learning easier, some of the key antenna characteristics, like gain and efficiency, are introduced much later in the chapter, after a discussion of the Yagi-Uda antenna.

Without doubt you will experiment with many types of antennas while you are listening and when you start transmitting. Every house, garden, or an apartment places restrictions but also offers opportunities that will guide your antenna choices. Whatever the circumstances, there will always be an antenna that suits them.

15.1 How do Antennas Work?

The RF AC containing information modulated by the transmitter is supplied by the transmission line to an antenna. It converts it into electromagnetic waves and radiates them into space. Antennas also perform the reverse: they convert electromagnetic waves travelling through space back into AC that represents the signals you are receiving.

The mechanism by which an antenna converts the AC into a freely travelling electromagnetic wave is surprisingly involved. It may be helpful to think of a simplified view of it. Imagine an electric field appearing between the two elements of an antenna, such as between the two lengths of a wire from which a simple dipole antenna is made. Because the RF AC is oscillating, it is constantly accelerating and decelerating the electrical charges (electrons) whilst changing their direction of travel. When the charges accelerate (or decelerate) they radiate energy as an oscillating electromagnetic wave propagating away from the antenna's wire.

For a more detailed discussion of the extraordinary processes that give rise to electromagnetic waves see the optional section 7.3 Fields and Wave Formation on page 72. Reading that section, even for the second time, would be useful while you are learning about antennas.

15.2 Near and Far Antenna Fields

The electric and magnetic fields created by an antenna react with the antenna itself before they become free of it. The immediate surroundings of the antenna contain the strongest EMFs. They are still attached to the antenna, pointing from and towards the antenna's wire, as shown in the very centre of Figure 7-ix on page 81. They are the NEAR FIELDS. The fields a little further away look very different. Although they are weaker, they become more parallel to the wire, no longer attached to the antenna, and starting to propagate away from it, as in Figure 7-viii on page 80. Those fields will travel far away from the antenna, perhaps around the Earth, or into space and to

the furthest parts of the universe. Those are the FAR FIELDS. The far fields are the ones you receive and listen to using your radio. The near fields, whilst essential to all antennas, can be a nuisance if your station is located too close.

There are three regions surrounding the antenna, somewhat confusingly referred to as ANTENNA FIELDS. Each of those regions is surrounded by the next one. As shown in Figure 15-i, there are no sharp boundaries, but each region has its characteristics.

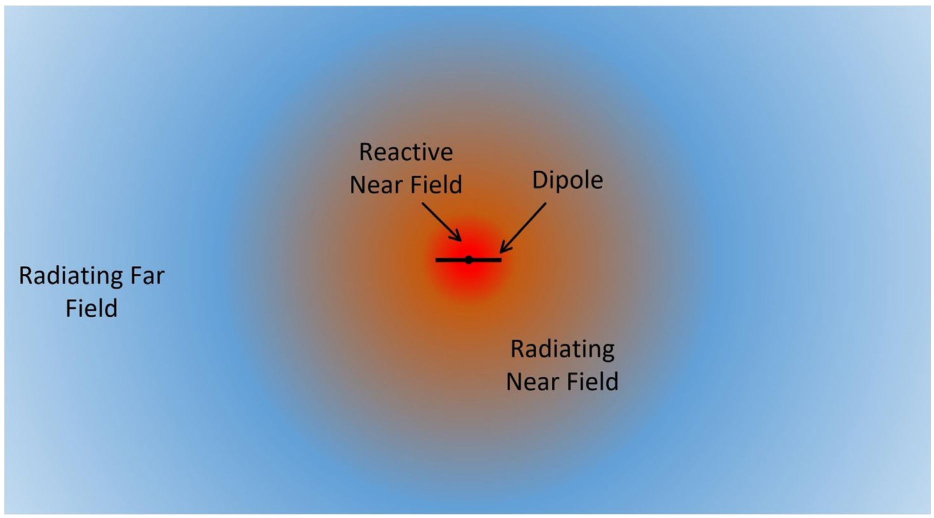


Figure 15-i: Fields surrounding a dipole antenna (black line in the centre): the reactive near field (red), the radiating near field (orange), and the radiating far field (blue). [EI9ILB]

- The REACTIVE NEAR FIELD, or simply the NEAR FIELD, immediately surrounds the antenna.[271] Either the electric or the magnetic field may dominate the other one in this zone at different points in space. There is no simple formula to calculate the strength of one from the other. Their shape and the pattern are related to the shape and the dimensions of the antenna, see Figure 19-iv on page 308 for an example. Most of the energy in this region is not yet radiating away as an electromagnetic wave, but it temporarily resides in the surrounding space while it reacts with nearby objects, which may dissipate, reflect, or otherwise affect the antenna in good and bad ways.[272]
- The RADIATING NEAR FIELD, or the INTERMEDIATE FIELD, is a transition zone between the reactive near and the radiating far fields.[273] The strength of the reactive field is rapidly decreasing in comparison to the fields radiated as the radio wave in

271 Also called the *induction field*.

272 An example of a good interaction is between the driven element and the reflector and the director in a Yagi antenna, which focus and direct the radio wave. Bad interaction would be reflection or absorption by metal structures and wiring of a nearby house, skewing radiation patterns, and potentially causing EMC problems.

273 Also called the *Fresnel region*.

this area. The transitional nature of this field is shown as the fuzzy orange area in the figure.[274]

- The RADIATING FAR FIELD, or simply the FAR FIELD, represents everywhere beyond the radiating near field, and it stretches out forever – it never ends.[275] Everywhere within the far field the electromagnetic wave radiated by the antenna has its fully formed behaviour explained in section 7.2 Electromagnetic Wave. The strength of the radiated electric and magnetic fields can be easily calculated from each other. They are perpendicular to each other, and they oscillate as a wave that is propagating at the speed of light (in vacuum). The shape of the expanding wavefront in now spherical, and no longer dependent on the shape of the antenna. The strength of the reactive fields is now so small that they are no longer detectable. The strength of the radiating wave is decreasing too, but the decrease is gentle compared to the reactive fields. As the distance travelled by the wave doubles, the strengths of the EMF only halves. They remain strong enough to be detectable at very long distances, as far as on other planets and even much further in the universe.

It is useful to understand the differences between the antenna fields for many reasons: to help you select, design, and build efficient antennas, and to understand how to troubleshoot some of their problems. Furthermore, the safety of any persons near an antenna directly depends on the frequency and the strengths of the electric and the magnetic fields surrounding the human body. They are strongest in the reactive near field, where they are also difficult to measure. As a rule of thumb for typical amateur radio power levels, it is preferable to avoid locating antennas if the general public could be present in its reactive near field. See 19.8 Non-Ionising Radiation and Electromagnetic Field Safety.

Although there are no sharp physical boundaries between the three regions, it is useful to know their approximate dimensions surrounding a half-wave dipole.

- Reactive near field — from the location of the antenna to between a quarter ($\frac{1}{4}\,\lambda$) and a half of the wavelength ($\frac{1}{2}\,\lambda$).
- Radiating near field — from the boundary of the reactive near field to about one wavelength, λ.
- Radiating far field — from the boundary of the radiating near field to infinity.

For example, using a half-wave dipole for the $\lambda = 40$ m band, which is about 20 m in length, the approximate boundaries would be: reactive near field ends and the radiating near field begins at approximately 10–20 m from the antenna; radiating near field ends and the radiating far field begins at about 40 m from the antenna.

Those simplified calculations only apply to a half-wave dipole being used on its design frequency: about 40 m in the case of a 20 m long dipole. If the same length is

274 The reactive fields are strongest near the antenna. Their *field strength* drops according to the *inverse square law*, or faster. As the distance doubles, it decreases to merely a quarter. Radiating field strength only halves as the distance doubles. This is a key difference between the *near* and *far* fields.

275 Also called the *Fraunhöfer region*.

used as a doublet antenna on a higher frequency, such as 20 m or 10 m, the fields are considerably further from the location of the antenna than the above distances.[276]

Other types of antennas, such as magnetic loops, or high-gain antennas, like a Yagi, will have significantly different distances to the boundaries between those regions. Knowing the boundaries will help comply with non-ionising radiation exposure limits, and it will help you troubleshoot interference and performance issues that may be caused by the presence of reactive or reflective objects in the near fields.

15.3 Feed Point Impedance

The RF AC that antennas transmit and receive is supplied to them from an attached transmission line, such as a coaxial cable, which were discussed in the previous chapter. The antenna terminal, or terminals, to which a transmission line is connected are known as the FEED POINT.

Just like a transmission line's characteristic impedance, antennas also have an important impedance property. It is called FEED POINT IMPEDANCE. It is the ratio of voltage to current at that point. It is determined by the antenna design. It is not determined by the transmitter or the feedline, which only control the amount of power that can be delivered to the antenna. The same antenna can have different feed point impedances on different frequencies. Since voltage and current are different at different points of the antenna's wire, the impedance also varies along the antenna. As a result, feed point impedance depends on the chosen location of the feed point.

In an ideal scenario, the feed point impedance of the antenna should be equal to the characteristic impedance of the transmission line, offering a perfect impedance match. That would permit a maximum transfer of power between the antenna and the line, without standing waves forming on the transmission line. See also 12.3 Output Impedance and 14.9 Impedance Matching and Transformation.

If connecting to commonly used coaxial transmission lines, the antenna's feed point impedance should be close to 50 Ω as possible. Otherwise, ATUs and impedance transformers can be installed between the antenna's feed point and the transmission line. Even if the impedances match, it is usually helpful to use a choke balun. See also 14.10 Antenna Tuning Units and 14.11 Baluns and Chokes.

15.4 Construction Materials

Antennas can be made from any conductive material. High conductivity materials, such as copper wire, or aluminium rods and tubes are the preferred choices. RF currents flow only on or near the conductor's surface. This is known as the SKIN EFFECT, see also footnote 256 on page 211. Because of the skin effect, antennas can be made

276 The formulae for the field boundaries depend on the antenna type. Boundaries of any dipole of a length D are: *near reactive boundary* $= 0.62\,\sqrt{(D^3/\lambda)}$ and *near radiating boundary* $= 2\,D^2/\lambda$. The same dipole of a length of 20 m used as a one-wavelength dipole on 20 m would have its near reactive field end at 12.4 m and its far radiating field start at 40 m.

from TUBING without reducing their performance while possibly aiding their mechanical strength.

Reflector-type antennas can be also made from a MESH as long as the holes are much smaller than the wavelength on which the antenna operates.[277] Mesh is useful for the design of some dish antennas, such as satellite antennas, because it prevents build-up of rain or snow from affecting their shape and performance.

15.5 Far Field Pattern

The FAR FIELD RADIATION PATTERN of an antenna shows directions in which the transmitted signal is likely to be strong. For a given antenna, it is identical to its CAPTURE PATTERN, i.e., a pattern that shows to which directions the antenna is more sensitive. Because the two patterns for a given antenna are the same, they are commonly just referred to as *the radiation pattern,* or simply as *the pattern.*

The far field pattern describes the electromagnetic wave travelling at large distances from the antenna. It is used extensively to discuss antenna performance. The near field patterns are differently shaped. Except for some special applications,[278] the near field patterns are used for antenna troubleshooting and safety assessments, see section 19.8. When you read or hear about the radiation pattern in amateur radio, it is invariably the far field radiation pattern being referred to.

Some antennas have distinct patterns that greatly favour one direction over another, such as the Yagi antennas. These are called BEAM ANTENNAS. It is convenient to summarise their pattern in numbers, gain and directivity, explained in this chapter.

Antenna modelling software can be used to plot radiation patterns of any antenna, including any design modifications. It is common to produce two plots: a horizontal plane and a vertical plane projection. Alternatively, a three-dimensional plot can be created and rotated using software to learn about the pattern of an antenna. Examples will be shown in section 15.8.1 Half-Wave Dipole Radiation Pattern.

15.5.1 Isotropic Antenna Radiation Pattern

An ISOTROPIC ANTENNA, also known as an ISOTROPIC RADIATOR, is a theoretical antenna that radiates electromagnetic waves equally in all directions from a single point in free space, far away from any ground, any other object. An isotropic antenna has no directivity, no gain, and its radiation pattern is a perfect sphere. It is shown in the three-

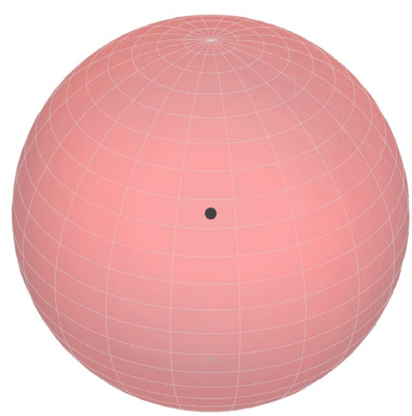


Figure 15-ii: Radiation pattern (red) of an isotropic antenna (black dot) is a sphere. [Image by Peter Zollman, see page 375]

277 At least 12 times smaller than the wavelength, e.g., 5 cm holes or less for the 70 cm wavelength.
278 Radio Frequency Identification (RFIDs), such as contactless payments, tolling tags, etc, are examples of near field communications.

dimensional plot in Figure 15-ii. The electromagnetic waves radiating from an isotropic antenna are equally strong in all directions.

Although this antenna does not exist in reality, it is used extensively to compare with real-world antennas. The concept of EIRP relies on it, see 15.20.

15.6 Polarisation

The POLARISATION of electromagnetic waves was discussed in section 7.8. By convention, the wave is said to be polarised in the direction of its electric field's lines of force. The direction of that field depends on the shape and the orientation of the antenna. For wire antennas, the polarisation of the wave matches the orientation of the wire. Vertical wire antennas produce vertically polarised waves, while horizontal wire antennas polarise electromagnetic waves horizontally.

When the transmitting and the receiving antennas have the same orientation, the transmitted EMF can exert its force in the direction that creates the strongest AC in the receiving antenna's wire. The received signals will be strong. This is particularly useful with line-of-sight propagation especially for VHF and UHF.

The polarisation of the waves can change when they are reflected or refracted from atmospheric layers. HF waves refracted from the ionosphere are no longer vertically or horizontally polarised, and the orientation of the antenna is less important.[279]

15.7 Half-wave Antenna

An important antenna type to study is a HALF-WAVE ANTENNA. It is just a length of a wire. It is designed to be used on a specific, narrow range of frequencies, for example, on the 20 m band. However, it can be also operated on the harmonics of that frequency, for example, on 10 m. The wire should be an electrical half wavelength of the design frequency because it will make it resonant at that frequency. The feed point impedance of a resonant antenna is purely resistive, with no reactance, and it easy to match it to the transmission line and the transmitter. See section 14.9 Impedance Matching and Transformation.

15.7.1 Voltage, Current, and Impedance on a Half-Wave Antenna

The voltage and the current are different at different points along the antenna. Their distribution on a half wave antenna is shown in Figure 15-iii. The voltage is highest at the ends of a half wave antenna, and reverses polarity at its centre.[280] The current is highest at the centre, and close to zero where the wire meets

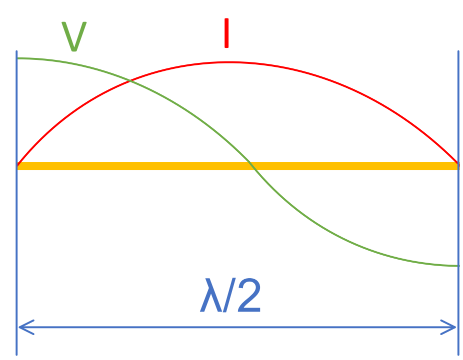


Figure 15-iii: Voltage and current profiles along a half-wave antenna. [EI9ILB]

279 They become *elliptically* polarised, with aspects of both horizontal and vertical polarisation.
280 Voltage is close to but not zero in the centre because real antennas have resistance.

the end.[281] Voltage is strongest (highest amplitude) even if it is negative. Because the voltage is highest at the ends, you should not touch the ends of an active half-wave antenna. You may receive an unpleasant burn, see 19.3.2 RF Burns from Direct and Near Contact with RF Currents.

The impedance of a resonant antenna is purely resistive. Since there is no reactance, impedance can be calculated as a ratio of voltage to current.[282] Because the voltage and current varies along the wire, the impedance will also vary at different points along the antenna. At the ends of a half-wave antenna, the current is low, and the voltage is high, yielding high impedance. At the centre, the current is high, and the voltage is low yielding low impedance.

The feed point impedance of a practical half wave antenna will also depend on its height above ground. For a horizontal resonant half-wave, the impedance is purely resistive and is about 74 Ω for an antenna in free space, but the impedance will vary as the antenna comes closer to ground. It can be either above or below the free space value. At heights below a quarter of a wavelength it will always be lower. It drops to about 40–70 Ω if the antenna is installed at a typical height above the ground.

15.7.2 Antenna Length

For the half-wave antenna to be resonant on a given frequency, it must be of a length that is equal to the ELECTRICAL HALF WAVELENGTH of that frequency.[283] Recall the approximate relationship between frequency f in MHz and wavelength λ in metres from section 5.1.3 Wavelength and Frequency.

$$\lambda = \frac{300}{f}$$

For example, the wavelength λ of a 14 MHz frequency is about:

$$\lambda = \frac{300}{14} = 21.4 \text{ m}$$

Notice that the 21.4 m is close to the common name for the 14 MHz band: the 20 m band. The half wavelength $\lambda/2$ is:

$$\frac{\lambda}{2} = \frac{21.4}{2} = 10.7 \text{ m}$$

10.7 m would be the free space half wavelength of the 14 MHz frequency, but this would not be its correct ELECTRICAL LENGTH when used as an antenna. Recall from 14.3.1 Electrical Length of a Line that to calculate the electrical length, the free space length needs to be multiplied by the velocity factor of the wire. The velocity

281 Current is not quite zero because of the *end effect:* capacitive coupling between the wire's end and the isolators and supports. Small amount of RF current will flow through them, like in any capacitor.

282 If there was any capacitive or inductive reactance, the calculation would yield a complex number. It would not be just a simple ratio of voltage to current. See 8.3.4 Impedance as a Number.

283 It will be also resonant if the length is close to an odd multiple (3, 5, ...) of that frequency. This also means that a half-wave antenna is resonant on its fundamental frequency and on its odd harmonics.

factor of a copper wire is 0.95–0.99, depending on the type of its insulation, making the electrical half wavelength slightly shorter than the free space wavelength.

Factors other than the length of the wire will also affect resonance of half wave antennas. A further reduction of the calculated length by about 5%, i.e., a factor of 0.95, should account for the capacitive effect of wire's end insulators. Taking it into account together with the velocity factor, the length of a 14 MHz half-wave antenna becomes about 10.06 m.

$$10.7\text{ m} \times 0.99 \times 0.95 = 10.06\text{ m}$$

In practice, a half-wave antenna's length would be further refined once installed to reach resonance to account for the proximity of supports and other nearby objects, and the way the wire is terminated and possibly looped at the ends.

Typical lengths of half-wave antennas are shown in Table 15-A. You do not need to memorise it, however, you should learn how to to calculate the approximate length of a half wave antenna for a given band or a frequency. Do not confuse the length with the band: a 20 m half-wave antenna is not a 20 m *long* half-wave antenna!

Table 15-A: Typical half-wave antenna lengths

Frequency (MHz)	Band (m)	Length (m)
1.8	160	75.2
3.5	80	35.2
7	40	20.3
14	20	10.05
21	15	6.7
28	10	4.93
50	6	2.85
70	4	2.02
145	2	0.97
430	0.7	0.32

15.8 Half-Wave Dipole

A half-wave dipole is one of the most popular antennas. It is also a fundamental design of an antenna on which all wire antennas are based, including advanced ones, like a Yagi. It is important to understand how it works and what are its characteristics.

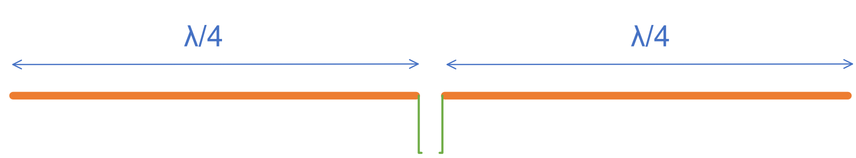


Figure 15-iv: Half-wave dipole. Antenna wire in orange, transmission line in green. [EI9ILB]

A HALF-WAVE DIPOLE is a half-wave antenna whose feed point is in the centre. The wire is cut in the middle, making each arm, also known as a leg, an electrical

quarter wavelength, so that they add up to the electrical half wavelength at the antenna's resonant frequency. Feed point impedance of a half-wave dipole is 30–80 Ω depending on its height above the ground. There are different ways to connect a transmission line to a half-wave dipole. A 1:1 balun at the feed point allows the use of a 50 Ω coaxial line.[284] See 14.11 Baluns and Chokes. It is also possible to use a parallel line of a different characteristic impedance, such as 75 Ω or 450 Ω, whose length is carefully selected to provide a desired impedance match for the transmitter on one particular band.

15.8.1 Half-Wave Dipole Radiation Pattern

The far field radiation pattern of a dipole depends on the height at which it is suspended over the ground. At the height of a half wavelength, $\lambda/2$, for example, at 10 m above perfect ground for a dipole designed for 20 m band, the pattern looks like an elongated ring doughnut, shown in Figure 15-v.[285]

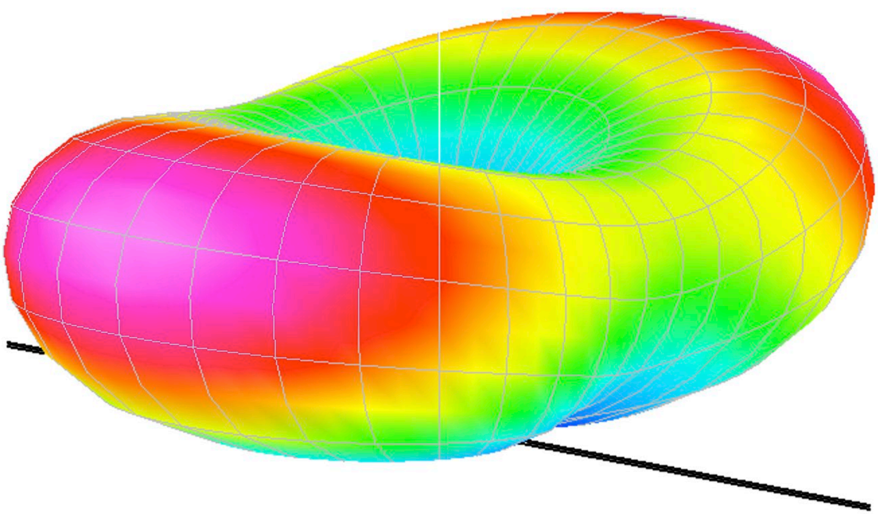


Figure 15-v: Far field radiation pattern of a dipole suspended at $\lambda/2$ height over perfect ground. Dipole position indicated by the black line under the pattern. Direction of the strongest radiation shown by purple (0 dB) and red (−1.5 dB), weakest in blue (−20 dB vs. purple). [EI6LA]

The three-dimensional plot shown in Figure 15-v uses colour to highlight the direction of the strongest radiation. The dipole's position is marked with the black line running from the left to the right, under the pattern. This dipole radiates strongest in the direction in front and behind the wire, perpendicular to it. Radiation towards the

284 A small mismatch will only have a negligible effect.

285 The radiation pattern greatly depends on the height above and the type of the ground because it reflects a vast amount of electromagnetic waves giving it the shape. Near perfect ground, such as the surface of a salty ocean, reflects everything. Otherwise, the pattern is a little different. Moving the dipole higher or lower than $\lambda/2$ will also change the pattern.

ends of the dipole is weaker. It does not waste power by radiating it vertically upwards. However, notice that the strongest radiation is slightly upwards, at an angle of about 30° above the horizon. While this can be seen in the 3D plot, it may be even easier to see in the two-dimensional VERTICAL PLANE plot shown in Figure 15-vi, which is also known as an ELEVATION PLOT. It shows the pattern as if you were standing at the centre of the dipole and looking along the length of the wire towards one of its ends. Compare it with the 3D plot, and you should be able to see a similarity. The vertical plane plot makes it clear that this dipole does not radiate vertically at all.

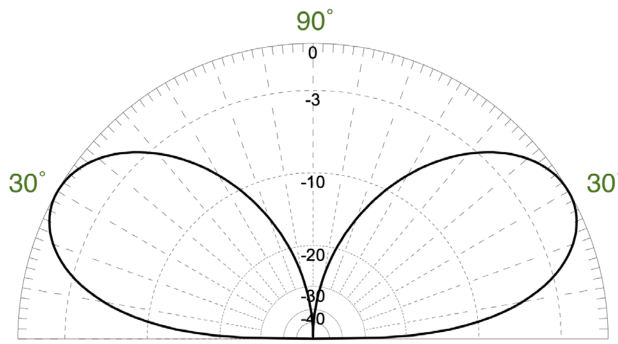


Figure 15-vi: Vertical plane radiation of a dipole at λ/2 height. Horizon at 0°, straight up at 90°. Viewed from the centre of the dipole. Strongest radiation in the direction about 30° above the horizon. Negative numbers show how much weaker is the signal, in dB, from the maximum. [EI6LA]

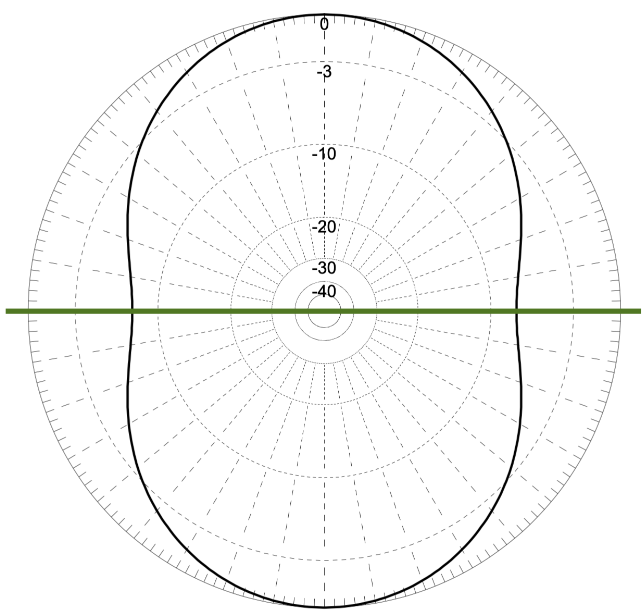


Figure 15-vii: Horizontal plane radiation of a dipole at λ/2 height. Viewed from above the dipole, shown as the green line, at 30° elevation above the horizon. Strongest direction towards the front of the dipole (top of the plot) and the rear (bottom of the plot). Radiation is -7 dB weaker towards the sides of than in front or behind it. [EI6LA]

Similarly, to see just how much stronger the radiation is in front rather than to the sides of the dipole, a HORIZONTAL PLANE plot is used. It is also known as an AZIMUTH PLOT. It is shown in Figure 15-vii. In that plot you are looking at the antenna wire, shown as the green line, from above, from an elevation of 30° above the horizon. That elevation was chosen for this plot because it is the direction of the strongest signal in the vertical plane. If the dipole wire was strung east-west, then the strongest direction of radiation would be towards the north and the south in this case.

As the plot shows, there is a significant increase of the intensity of the radiation towards the front and back in comparison to the sides of this dipole. Compared to an isotropic antenna, whose pattern is perfectly spherical, the dipole's improvement looks even higher. This is DIRECTIVITY, and it is explained in more detail in section 15.15. By examining a combination of horizontal and vertical radiation plots it is possible to understand the directivity of an antenna and locate it to its best potential. The 3D plot is particularly helpful if it can be interactively rotated by the viewer using antenna modelling software.[286]

15.8.2 Vertically Oriented Dipole

The half-wave dipole discussed above was oriented horizontally above the ground. It is also possible to orient them vertically, especially on higher frequencies, such as VHF and UHF, when they are physically smaller. Their radiation pattern would be different from that shown above. It would favour long-distance communication by having a shallower angle of maximum radiation. See also its close relative in section 15.13 Quarter-Wave Ground Plane Antenna (Vertical).

15.9 Non-resonant Wire Antennas and Multiband Antennas

If the length of a half-wave antenna is the electrical half wavelength of the frequency of operation, i.e., its fundamental frequency, that antenna is resonant on that frequency. Its impedance is only resistive with no reactance.[287] What happens, however, if an antenna is only a little shorter or longer than an electrical half wavelength of its fundamental frequency?

If the antenna wire is a little shorter than the electrical half wavelength of the frequency of operation, it will no longer be resonant. It will have *capacitive* reactance, as well as resistance at the feed point. On the other hand, if the antenna is a little

286 Plots shown in this guide were generated using GAL-ANA and MMANA-GAL, see gal-ana.de. See also EZNEC www.eznec.com, also for Windows. For Linux/Unix users, Xnec2c at www.xnec2c.org. These programs rely on the widely used Numerical Electromagnetics Code (NEC) computation engine, see en.wikipedia.org/wiki/Numerical_Electromagnetics_Code.

287 It will be also easy to use on frequencies that are odd harmonics (3rd, 5th, …) of the fundamental frequency. A half-wave dipole resonant on 7 MHz will be close to resonant on 21 MHz. The feed point impedance will be close the fundamental. However, its pattern will be different at this height. See footnote 290 about even harmonics.

longer than the electrical half wavelength at the frequency of operation, it will have *inductive* reactance, as well as resistance at the feed point.[288]

Such antennas can be used successfully – there is nothing inherently special about resonant antennas. Both resonant and non-resonant antennas radiate equally well. If the mismatch is small, it requires no special treatment, because the level of SWR that it would cause would be insignificant.[289] A significant mismatch can also exceed equipment limitations, especially of solid-state transmitters and amplifiers that often require a load impedance close to 50 Ω. On longer transmission lines, it may be also difficult to efficiently transfer power because of the losses. See 14.9.3 Standing Waves on a Transmission Line and Line Loss.

To efficiently transfer power the feed point impedance of a non-resonant antenna needs to be matched to that of the transmission line and the transmitter or a receiver. This is commonly accomplished using an ATU, see 14.10 Antenna Tuning Units, or a transformer balun. Finding such a match is usually possible even with high levels of an impedance mismatch.[290]

NON-RESONANT DIPOLES are very popular.[291] Their length is usually chosen to be the half wavelength of its lowest design frequency. For example, a 35 m long half-wave dipole for the 3.5 MHz (80 m) band can be also used on higher frequency bands, such as the 10 MHz (30 m) band. Such a dipole will present acceptable feed point impedance on some, but not on all of those bands. Combined with an ATU, however, it can be successfully used as a MULTIBAND ANTENNA.

Radiation patterns of non-resonant wire antennas are quite different to that of a half-wave dipole, especially when operated on frequencies whose half wavelength is much higher or lower than the height of the antenna above the ground.

One of the most popular non-resonant dipole designs, the G5RV antenna, employs a length of a parallel transmission line as an impedance transformer. It can be fed with a 50 Ω coaxial line and used on several bands with the resultant SWR below 4:1 even without an ATU.[292]

288 If an antenna length is further away from $\lambda/2$, approaching a full wavelength, λ, it behaves the opposite way. It becomes capacitive when slightly longer than λ and inductive when shorter, up to the point when it is yet another half wavelength. In other words, looking at the $\lambda/2$ lengths and their odd multiples, the antenna is capacitive when shorter and inductive when longer around those points.

289 Technically, an antenna is resonant on exactly one specific frequency. Every other one, even within a single band, is no longer resonant. No antenna can be resonant on an entire band, especially not on MF or LF. *Resonance* is a loose term in amateur radio. The mismatch is usually insignificant.

290 It is harder on frequencies that are even harmonics (2nd, 4th, ...) of the fundamental. The antenna is once again resonant, i.e., it has no reactance, however, its purely resistive impedance is very high, possibly exceeding the design of the ATU or a balun. A half-wave dipole resonant on 7 MHz may be harder to match on the 14 MHz frequency, even though it is resonant.

291 By convention, non-resonant dipoles are sometimes called *doublets*. However, doublet is technically a synonym of a dipole. Check the intended meaning when reading literature that mentions both.

292 With an ATU a G5RV becomes almost an all-band antenna, however, with compromised radiation patterns. It is worth considering as a single, simple, inexpensive wire antenna, tolerant of different installations, including inverted-V, and which works on so many bands. Other versions, like ZS6BKW, use slightly different dipole and feeder lengths to optimise the performance on different HF bands.

15.10 End-Fed Half-Wave Antenna

An END-FED HALF-WAVE ANTENNA, EFHW, is a half-wave antenna whose feed point is at one of the ends of the wire. The end of the wire can be partly bent and brought closer to a convenient location for the connection to the transmission line. An example of how this antenna can be built is shown in Figure 15-viii.

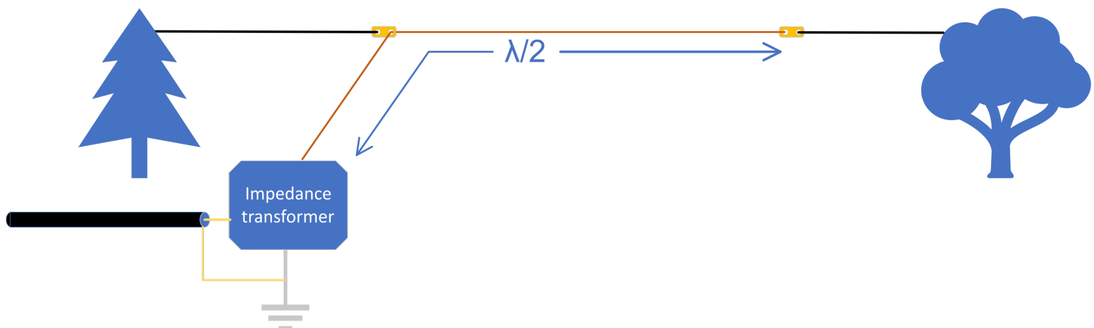


Figure 15-viii: End-fed half-wave, EFHW, antenna installation. Note the RF earth shown with the grey symbol below the impedance transformer. [EI9ILB]

If the antenna wire is kept horizontal, rather than bent, the radiation pattern of an EFHW is almost the same as that of a dipole. Bent wire will change that pattern somewhat, potentially making it more omnidirectional.

The voltage, and therefore the impedance, are highest at the ends of a half-wave antenna, reaching many thousands of ohms.[293] An impedance transformer is necessary to match such a high feed point impedance to that of a coaxial transmission line. This can be accomplished using a suitable impedance transformer, such as a 49:1 unun (see 14.11.3), or, depending on the length of the antenna wire, a 9:1 unun, which may be able to cover several harmonically related HF bands.[294] When using fixed impedance transformers an ATU is usually necessary.

For the EFHW to work well, an RF earth may also be necessary. Such earth needs to be connected to the impedance transformer and to the outer conductor of the coaxial transmission line.[295]

Electric field strength in the reactive near field of any half-wave antenna, including EFHW, is strongest at the ends of the antenna. If one of the ends of an EFHW is close to the radio room, or any other building, it is very likely that the strong electric field will cause EMC issues, including interference with susceptible equipment, computer cables, and any poorly shielded equipment. For similar reasons, the impedance

293 The feed point impedance of an EFHW is high and difficult to predict. It depends on the lengths of the wire, especially the very short fragment connecting the RF earth. It varies between 1000–5000 Ω.
294 For broadband HF coverage using a non-resonant length of wire, it may be better to use a 9:1 unun, although such design is no longer a typical EFHW.
295 If the feed point is elevated above ground and it is difficult to provide RF earth, a short length of a wire can be used as a kind of a counterpoise. This alternative solution is likely to affect the resonant frequencies, and it will cause considerable common mode currents on the feedline.

transformer, and the end of the EFHW antenna should be located as far away as practical from the building, ideally so that people and the equipment are not in the near reactive field of the antenna.

Because the voltages are highest at the ends of half-wave antennas, care must be also taken to avoid the possibility of people or animals coming close to it or touching it when operating. Ideally, the ends of the wire should be at least 2.4 m out of reach of a person or an animal.

15.11 Folded Dipole

The FOLDED DIPOLE antenna has an additional half wavelength wire placed close to the main wire and connected at their ends, as shown in Figure 15-ix. Although it can be used on any frequency, this design is particularly popular with VHF and UHF antennas, using tubing instead of wires.

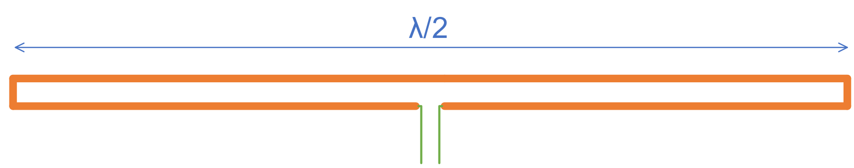


Figure 15-ix: Folded dipole. Two wires (orange) connected at ends. Transmission line (green) connected to the feed point in the centre. [EI9ILB]

The folded dipole has the same radiation pattern as a dipole. However, it has two additional properties. It presents a higher feed point impedance than a simple dipole. Its feed point impedance is approximately 300 Ω which makes it convenient to connect to popular parallel lines, such as those shown in Figure 14-iii on page 210. It also works on a broader range of frequencies than a simple dipole while maintaining a similar feed point impedance. In practice, this means that it will cause a smaller increase of SWR on the attached transmission line whilst changing frequencies than a simple dipole would. Unlike a dipole or an EFHW, the folded dipole will not operate well on harmonics of the resonant frequency.

An antenna, such as a folded dipole, that can serve a wider range of frequencies without affecting the feed point impedance and, therefore, the SWR, is known to have a wider BANDWIDTH.[296]

Feed point impedance of a folded dipole can be adjusted by varying the diameter and the spacing of the two conductors, or by adding additional, third or more, conductors.

296 On the other hand, there are antennas that have a much narrower bandwidth, too. Small *magnetic loop* antennas have such a narrow bandwidth that they require an adjustment to the antenna itself whilst changing frequencies. This can be inconvenient, but also advantageous because narrow bandwidth antennas naturally reject frequencies outside of their currently selected bandwidth, making them useful in environments with high levels of RF noise.

15.12 Trap Dipole

A TRAP DIPOLE can be a dual-band or a multiband antenna. Let's focus on the dual-band design, for a lower and a higher frequency band. The lower of the two bands is served by the overall length of the wire, and the higher band by the shorter length between the two traps, as shown in Figure 15-x.

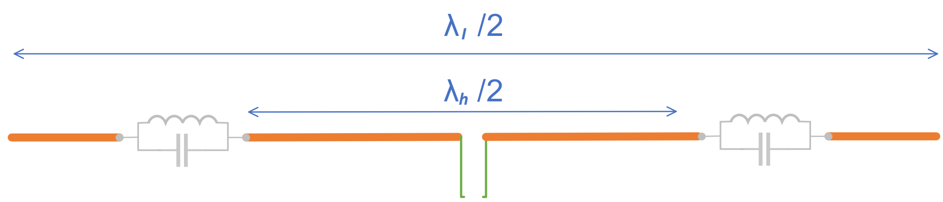


Figure 15-x: Trap dipole for two bands, whose wavelengths are λ_l and λ_h [EI9ILB]

The TRAPS are parallel resonant circuits connected in series that act as band-stop filters, see 8.4.1 Series and Parallel LC Circuits. They can be made from an inductor (coil) and a capacitor. Their resonant frequency is on the higher of the two bands of the antenna. That higher frequency band is served by the shorter λ_h section of the dipole.

Let's discuss how this antenna could be built for the $\lambda_h = 20$ m and the $\lambda_l = 40$ m bands, 14 MHz, and 7 MHz, respectively. For the higher frequency of 14 MHz, the resonant length of the central wire is about 10 m in total. The traps are designed so that they resonate at the higher frequency 14 MHz, presenting a high impedance to the RF AC at that frequency. They isolate the remaining lengths of the wire at 14 MHz, so only the central section is in use.

However, on the lower frequency of 7 MHz the traps no longer act as a band-stop filter. The additional sections of the wire are electrically connected to the central section when operating on the lower frequency. The whole length λ_l of the wire is in use. Because the traps appear as inductors at the lower frequency, they add to the electrical length of the wire. As a result, to make the whole antenna resonant at 7 MHz those additional sections of the wire need to be somewhat shorter.

By modifying or adding additional traps this dipole can serve more bands, becoming a multiband antenna that is resonant on all the bands it serves, and possibly not requiring an ATU.

Just like non-resonant multiband antennas, the radiation patterns of a trap dipole will be different on different bands. This happens because the electrical length and the height of the antenna above the ground are fixed with regards to the different wavelengths it serves.

15.13 Quarter-Wave Ground Plane Antenna (Vertical)

A QUARTER-WAVE GROUND PLANE ANTENNA is a vertical antenna, whose length is a quarter of the wavelength on which it is operated. It is also known as a MONOPOLE. It works like a vertically oriented half of a dipole placed on a reflector. The

role of the reflector can be played by the earth, a metal sheet, or several wires, forming a GROUND PLANE. Those reflectors fulfil the role of the *missing* half of a dipole, although they can never succeed completely in doing that. Figure 15-xi shows a quarter-wave vertical ground plane antenna. There are two popular arrangements of the wires forming the ground plane: RADIALS placed on the ground, or a COUNTERPOISE elevated above it, in the air.

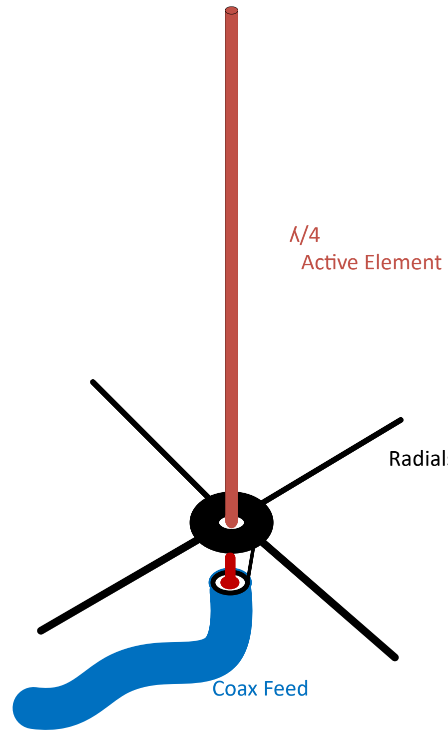


Figure 15-xi: Quarter-wave, λ/4, ground plane vertical antenna with four radials. [EI9ILB]

Unlike previously discussed dipoles, a quarter-wave ground plane antenna can be directly fed with a coaxial cable, see 14.6 Coaxial Line. The centre conductor is connected to the active vertical element, while the outer conductor is connected to the radials or the counterpoise and, as normal with coaxial transmission lines, to the earth.[297] The radials or the counterpoise are *not* connected to the active element.

Even though it is not necessary to use a balun when connecting this antenna to coax, a balun fulfilling the role of a choke is sometimes recommended. Quarter-wave ground plane vertical antennas have several interesting characteristics.

- Small footprint means they fit in smaller spaces, as long as they are properly supported. Some designs, using tubing, are self-supporting.
- The vertical element is only quarter of the wavelength long, which is lower than the half wavelength height required for good dipole performance.
- A vertical of any convenient height can act as a very effective multiband HF antenna if used with a good set of ground radials and an ATU at the base.
- The radiation pattern is suited for long distance HF communication because the strongest direction of radiation is at a shallow angle with respect to the horizon.

297 This is an example of an unbalanced antenna, a historical term used to describe antennas which do not have two symmetrically placed elements carrying identical but opposite currents, with equal impedances with regards to ground. This is a somewhat confusing term, however, because the currents in the vertical element will be balanced in some sense of that term by those in the ground plane. Also, it could be argued that all vertical antennas are unbalanced because one side is inevitably closer to ground than the other. For reasons such as these, the balanced vs. unbalanced terminology is becoming less popular.

The radiation pattern is OMNIDIRECTIONAL in the horizontal plane, i.e., it radiates with the same intensity all around its vertical element, as shown in Figure 15-xii and, perhaps more clearly, in Figure 15-xiv on the next page, where the pattern is clearly a perfect circle that does not favour any direction.

As those figures also show, especially in Figure 15-xiii, the strongest direction of radiation in the vertical plane is at 20° over the horizon, assuming a near perfect ground underneath, which may not be present in many locations. It is that shallow angle of radiation that makes these antennas desirable for long-distance HF communication that benefit from ionospheric sky wave propagation, see 16.5.2 Sky Wave.

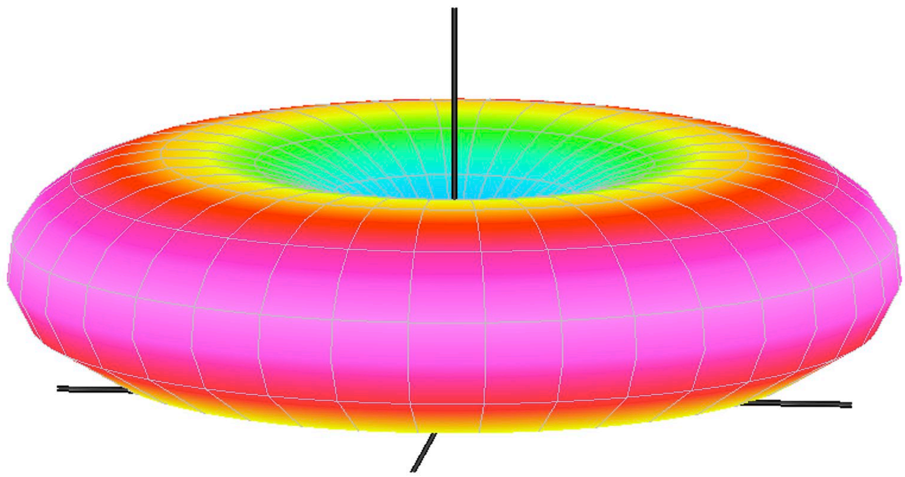


Figure 15-xii: Radiation pattern of a quarter-wave ground plane antenna with elevated radials (counterpoise). Strongest direction indicated in purple and red. The vertical and radial antenna elements in black. [EI6LA]

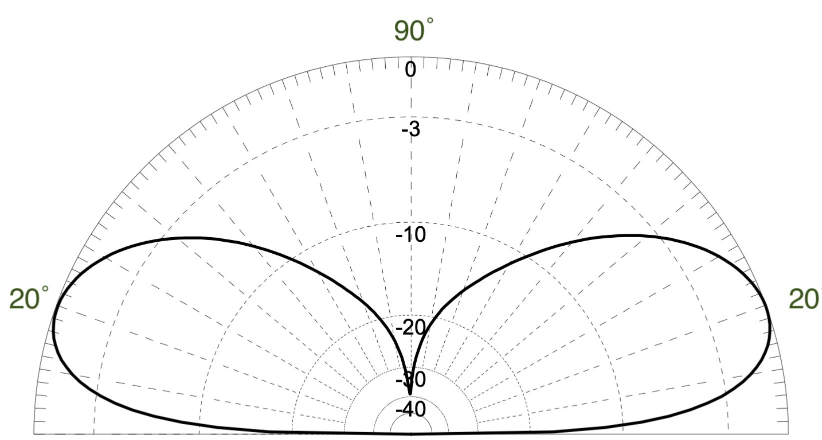


Figure 15-xiii: Radiation pattern in the vertical plane of a quarter-wave ground plane antenna with four elevated radials. The strongest signal is radiated in the direction of 20° above the horizon, as seen from its vertical plane pattern on the left, assuming perfectly reflective counterpoise. [EI6LA]

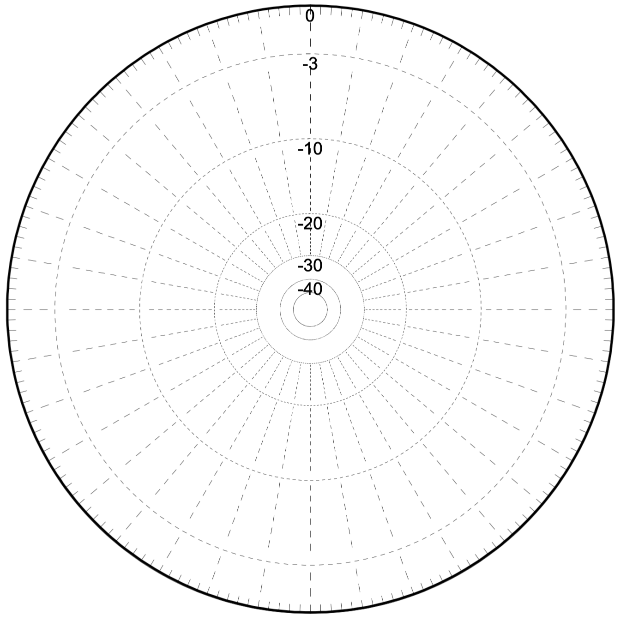


Figure 15-xiv: Radiation pattern in the horizontal plane of a quarter-wave ground plane antenna with four elevated radials. This antenna is omnidirectional, as can be seen from the circular pattern. [EI6LA]

15.13.1 Quarter-wave Vertical with Radials on the Ground

The radials can be placed on the ground, or they can be partially buried. In this design, the antenna needs to be quite close to the ground, too. The feed point impedance of this design is about 35 Ω.

This is a very popular design for vertical HF antennas. To be effective, this design requires a considerable number and length of the wires used for the radials. There are formulas for calculating the number and the lengths of the radials.[298]

15.13.2 Quarter-wave Vertical with Elevated Radials (Counterpoise)

By using radials elevated above the ground, also known as a counterpoise, the entire antenna can be raised, too. This is a popular design for 2 m VHF and 70 cm UHF vertical antennas. When radials are in the air, a smaller number is required than when laid over the ground. Their usual length is $\lambda/4$. The feed point impedance increases with this design. By drooping the radials at angle of about 25–30° the feed point impedance reaches 50 Ω, allowing for a perfect impedance match to coaxial transmission lines and the equipment. A disadvantage of downward-tilted radials is that strong common mode currents will find their way onto the outside of the feedline, making the actual vertical radiation pattern uncertain.

298 Four radials is the realistic minimum, as short as λ/10. It will function better with more radials, but improvements are small from a dozen onwards. Counterintuitively, if using more radials, they should be longer, λ/4. Commercial radio stations use as many as 128 radials and a wire mesh on the ground.

15.14 Yagi-Uda Antenna

The YAGI-UDA ANTENNA, named after its inventors, is usually referred to as a Yagi.[299] It is based on a half-wave dipole, which in a Yagi is known as the DRIVEN ELEMENT. It has the feed point at its centre, just like a half-wave dipole, which is the only element in a Yagi that is connected to the transmission line.

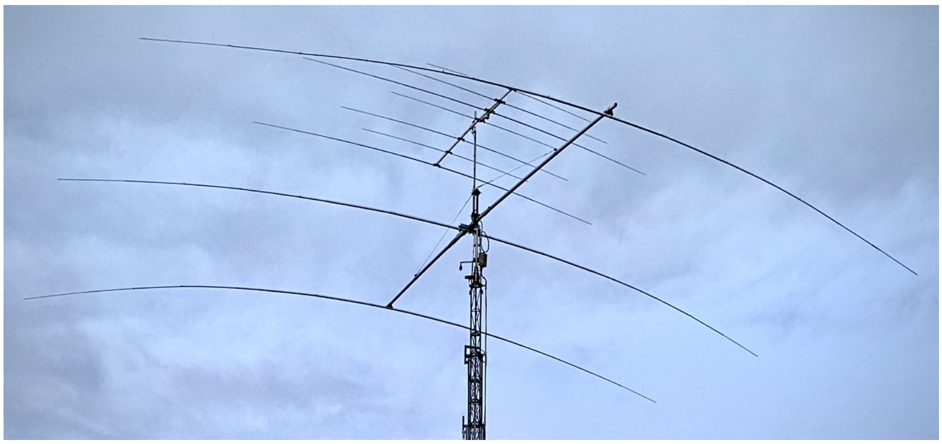


Figure 15-xv: A 3-element, 40 m band Yagi-Uda antenna. Note that the other, 7-element beam antenna mounted above it, has a different, more complex design, which combines several Yagi-Uda antennas for use on multiple bands. [EI6LA]

A Yagi also uses one or more additional wire elements, not connected to the feed line, as shown in Figure 15-xvi. Please note that the boom supporting the elements together is not shown in this drawing. Those additional elements are known as PARASITIC ELEMENTS. The longer one at the back acts as a REFLECTOR, and the shorter ones at the front as DIRECTORS of the electromagnetic waves. They give the Yagi its much desirable quality of being a DIRECTIONAL ANTENNA, able to focus the radiation in the direction of interest. Yagis and similar directional antennas are also known as BEAMS because of their ability to focus, or beam, radio waves transmitted to and received from the chosen direction.

They need to be rotated towards the destination or towards the source of the transmitted or received signals. They are usually mounted on masts using remotely operated ROTATORS.

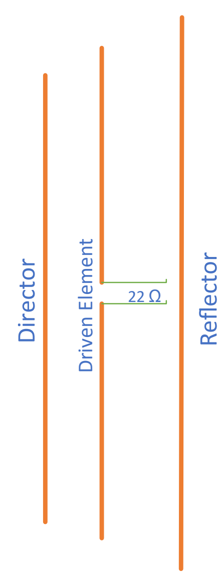


Figure 15-xvi: Elements (orange) of a Yagi antenna. Front on the left, back on the right. [EI9ILB]

299 The Yagi-Uda antenna was invented in 1926 by Shintaro Uda and Hidetsugu Yagi of Tohoku Imperial University, Japan. It was used for radar systems before becoming the most popular TV antenna.

The length and the spacing of the parasitic elements are such that they reinforce the radiation in the direction of the director and reduce it in the opposite direction.

The most common design is a three-element Yagi, as shown in Figure 15-xv, on the lower section of the mast. It has one reflector, and one director element, in addition to the driven element, the half-wave dipole.[300]

One of the additional elements is approximately 5% longer, and several others are 5% or progressively shorter than the driven element. A diagram of this design is shown in Figure 15-xvii. Learn to identify elements of a Yagi antenna, as it will help you point it in the correct direction. You do not need to remember their exact lengths or distances for the exam.

Being a dipole, a Yagi antenna has two connectors at its feed point.[301] It requires a device, such as a balun, for connecting to a coaxial line. Feed point impedance of a three-element Yagi is about 20 Ω. The driven element can be also a folded dipole. This has the effect of raising the feed point impedance to make it a better match for a coaxial transmission line.

Alternatively, an impedance matching device known as a GAMMA MATCH can be used to give an almost perfect match to a 50 Ω coaxial cable.

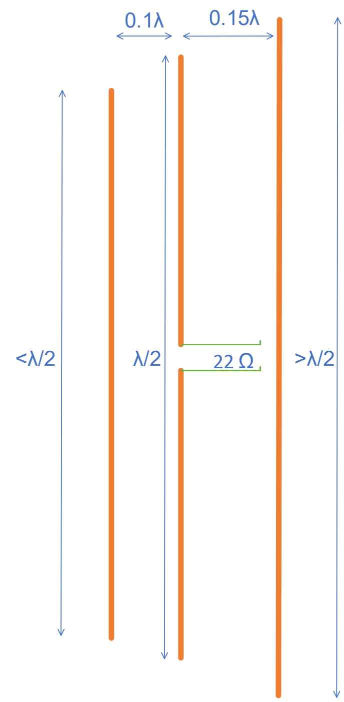


Figure 15-xvii: Lengths and positions of the elements of a three-element Yagi antenna. Front to the left, back to the right. [EI9ILB]

15.14.1 Yagi Radiation Pattern

The radiation pattern of a Yagi antenna, like of any dipole, depends on its height above the ground. Towers of a suitable design are necessary to support such antennas and their rotators, especially for the lower frequency bands: a Yagi for 7 MHz needs to be at 20 m above the ground to be at the $\lambda/2$ height, which is the desirable minimum, and at 40 m for the full wavelength height!

Three-dimensional far field radiation patterns of a three-element Yagi are shown. Figure 15-xviii shows a Yagi at half wavelength, $\lambda/2$, height, while Figure 15-xix shows it at the one wavelength, λ, height above ground. Black lines under the pattern plot represent the three antenna elements. Please note that the boom that holds the three elements together is not shown because it is not part of the antenna.

300 Two-element Yagis also exist, with the driven element and only a reflector or a single director, but the three-element is the simplest Yagi that provides a worthwhile return on the cost and the effort.

301 It belongs to the historical category of balanced antennas.

As the plots show, Yagi favours the direction towards the front, where the director element(s) are. On the other hand, there is very little radiation at the back of it, where the reflector is. The same principle will apply to received signals. The Yagi will hear signals coming from in front of it much better than those from behind, or from the sides.

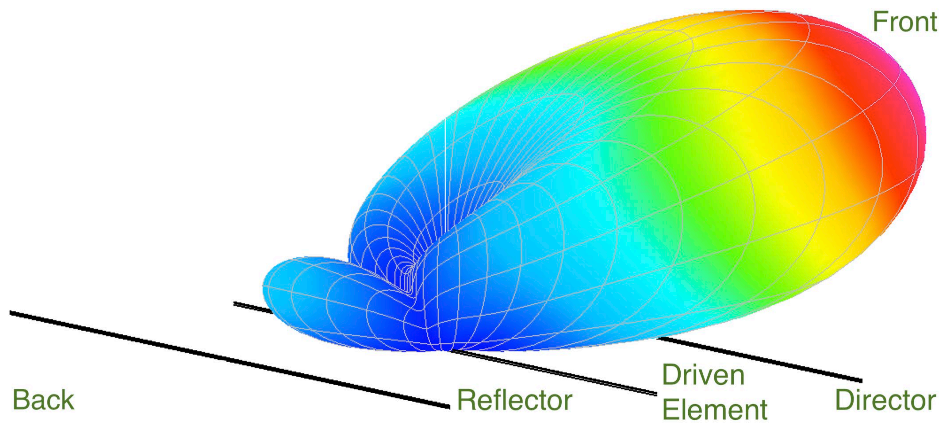


Figure 15-xviii: Far field radiation pattern of a three-element Yagi installed at half wavelength, $\lambda/2$, height over a perfect ground. Purple and red indicate the direction of the strongest radiation, blue the weakest. [EI6LA]

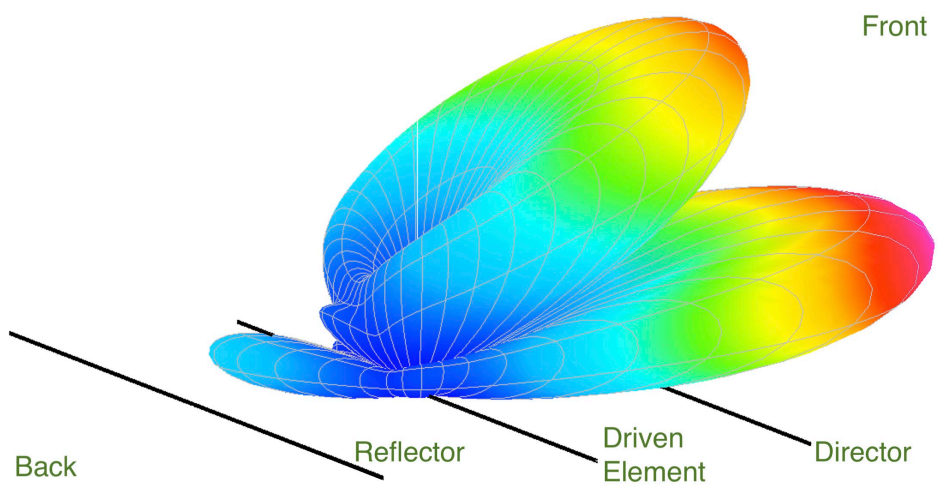


Figure 15-xix: Far field radiation pattern of a three-element Yagi installed at one wavelength, λ, height over a perfect ground. [EI6LA]

The differences between the two heights are clearer to see in the two-dimensional plots shown on the next page. Figure 15-xx shows the Yagi at half wavelength, $\lambda/2$, height, while Figure 15-xxi shows it at the one wavelength, λ, height.

The horizontal plane plots, on the right, show that there is almost no difference between the horizontal patterns at these two heights. The main difference between

the heights is in the vertical pattern. The lower λ/2 height focuses the strongest radiation in the direction of just under 30° above the horizon. Raising the height of the antenna to λ above ground has an effect of creating two LOBES of radiation, one directed 45° and one 15° above the horizon. It is the presence of this shallow, low angle 15° above the horizon radiation lobe that makes this design particularly useful for long-distance HF communication, see 16.5.2 Sky Wave. The obvious drawback, visible in these plots, is the introduction of a significant reduction of strength at 30° which will reduce performance at intermediate distances.[302]

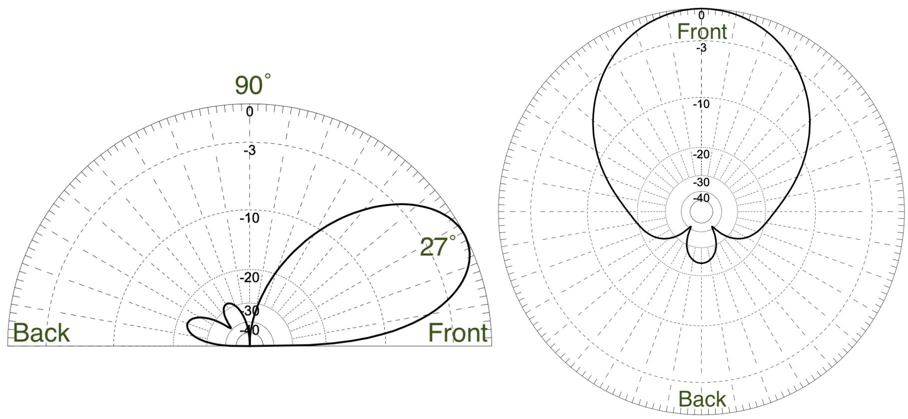


Figure 15-xx: Vertical (left) and horizontal (right) radiation pattern of a three-element Yagi at half wavelenght, λ/2, height. Note the approximately 27° above the horizon vertical direction of maximum radiation. Notice also how almost all the radiation is in front rather than behind the antenna. [EI6LA]

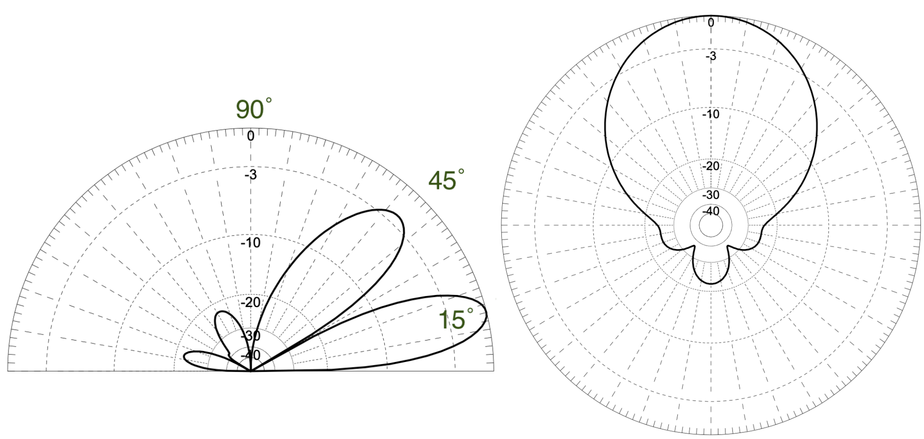


Figure 15-xxi: Vertical (left) and horizontal (right) radiation pattern of a three-element Yagi at one wavelenght, λ, height. Note the lowest angle of radiation is now at 15° above the horizon. Notice that there is almost no difference to the front vs. back horizontal pattern, compared to λ/2 height shown in Figure 15-xx. [EI6LA]

302 Such a significant reduction is known as a *deep null*.

Both horizontal plane plots show how directional the Yagi is. Taking the top of the plot as the direction in front of the antenna, marked at the 0 dB level, the radiation towards the sides and the back of the antenna is much smaller. At the back, it is more than 20 dB weaker than in the front, i.e., it is over 100 times weaker behind than in the front, or, in terms of S meter readings, a difference of almost 4 S points. This is known as the front-to-back ratio, and it will be explained in more detail in 15.16. See also Chapter 9 Power Ratios and Decibels and section 13.3.11 S Meter.

15.15 Directivity, Efficiency, and Gain

Recall from 15.5.1 that an isotropic antenna radiates equally well in all directions. Any other, real-world antenna tends to radiate better in one direction than another. As shown earlier in 15.8.1 Half-Wave Dipole Radiation Pattern, that dipole radiates much better perpendicularly towards the front and the back of the wire than to its sides. A Yagi has an even more pronounced radiation pattern, as shown in the previous section. An important aspect of the directivity of an antenna is that it affects transmission and reception equally well. Signals coming from the direction of the maximum radiation pattern will be stronger than those coming from other directions.

Directivity and gain are closely related characteristics that summarise how directional an antenna is. They are both ratios, and they are expressed in decibels (dB). They are used to compare an antenna to a *reference* antenna, normally the isotropic antenna or a half-wave dipole in FREE SPACE, i.e., far away from the ground, any objects, and away from the influence of any other sources of EMF.

The DIRECTIVITY is the ratio of the intensity (field strength or power density) of electromagnetic radiation in the maximum direction compared to a reference antenna.[303] Directivity tells us how much stronger the radiation is in the antenna's most favourable direction compared to a chosen reference antenna.

The GAIN is the directivity less any inherent antenna losses, which are related to the antenna's radiation efficiency. Gain of all practical antennas is always a little less than their directivity.

The EFFICIENCY of an antenna is a factor that determines what percentage of power supplied to the antenna is radiated as electromagnetic waves.[304] The rest is wasted as heat. Large antennas, such as half-wave dipoles and Yagis, are generally very efficient. Their radiation efficiency usually exceeds 95%. As a result, there is almost no difference between their gain and directivity. Some antennas, such a small magnetic loops, have a much lower gain than directivity.[305] Also, antennas mounted close to ground are likely to have significant losses due to energy wasted on inducing circulating currents in the ground itself.

303 Although power density is different from field strength, their ratio will be the same.

304 Efficiency, k, of an antenna is the ratio of power radiated to input power, $k = P\,radiated / P\,input$. If all is radiated, the ratio is 1, or 100%. Gain $G = kD$. It combines directivity, D, with efficiency, k.

305 The idealised isotropic antenna has perfect radiation efficiency and no losses. Dipoles and Yagis are not far off. Other antennas, such as *small* magnetic loops, can be quite inefficient, especially on the lower frequency bands, converting as much as 30–75% of power into heat, rather than radiating it. Their directivity is similar to a dipole, but their gain is smaller because of the losses.

It is common to express gain and directivity in comparison to either the isotropic antenna, which radiates equally in all directions, or to a half-wave dipole in free space which by itself has some directivity and gain over the isotropic antenna. Figure 15-xxii shows the difference between the two types of gain:

- dBi — gain relative to the isotropic antenna
- dBd — gain relative to a half-wave dipole in free space

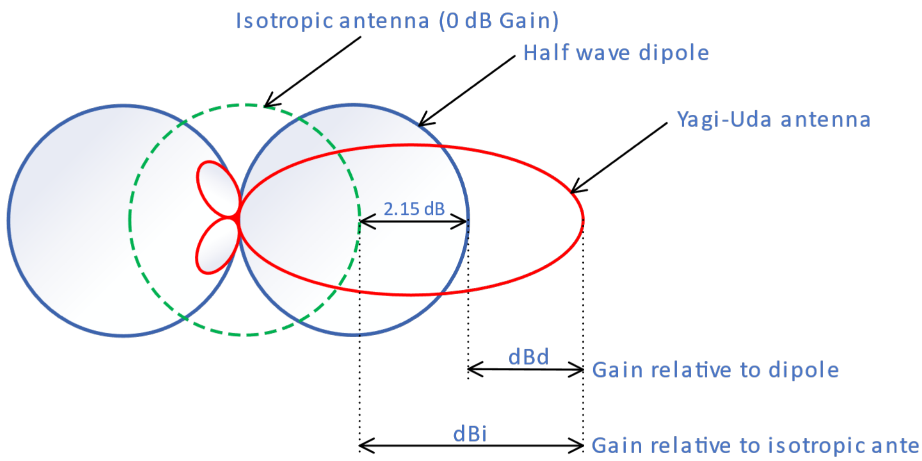


Figure 15-xxii: Yagi gain relative to an isotropic antenna, dBi, and relative to a half-wave dipole in free space, dBd. [EI9ILB]

- An isotropic antenna has no directivity or gain. Its gain and directivity are 0 dB.
- A half-wave dipole in free space has 2.15 dB gain over an isotropic antenna.[306]

$$\text{dBi} = \text{dBd} + 2.15\ \text{dB}$$

The theoretical free space gain of a three-element Yagi antenna over a half wave dipole is about 7 dBd. It is about 9 dBi, i.e., relative to the isotropic antenna.

The gain of this Yagi if installed at the height of one wavelength over the ground would be even larger, 13 dB. That means the transmitted signal would be over twenty times stronger in that direction than from an isotropic antenna fed with the same amount of power. See also 9 Power Ratios and Decibels. With such a significant gain, just 100 W of power fed to that antenna will be focused as if it were a 2 kW isotropic antenna.

! Do not stand directly in front of an active high gain antenna such as a Yagi on a ladder, mast, or a balcony, and do not point it at people or animals, if fed with considerable power.

306 A half-wave dipole at $\lambda/2$ height over a perfect ground has an 8 dBi gain, or about a 6 dBd gain. That means a dipole at a typical height over the ground has a gain of about 6 dB over a dipole in free space.

! Avoid standing close to physically small antennas such as HF magnetic loops because both the electric and magnetic fields are strongly concentrated within and around them.

By mounting antennas sufficiently high you can eliminate the risks of exceeding safety exposure limits. See also 19.8.5 Estimating and Modelling RF Field Strengths and Exposure.

Adding more director elements to a Yagi increases its gain and reduces its angle of lowest radiation, making it even more appropriate for long-distance communication.[307]

Because gain and directivity also apply to reception, signals coming from the favoured direction will also be stronger than those from other directions.

15.16 Front-to-Back Ratio

Any antenna's gain in one direction is always compensated by a reduction in other directions because while antennas can focus the radiation energy, they cannot make it from nothing. In the case of a Yagi, the radiation from the back of the antenna is much weaker than from the front of it.[308]

The ratio of the intensity of the radiation in the maximum forward direction to the intensity in the back is the FRONT-TO-BACK RATIO.[309] It is expressed in dB. It can be easily calculated by subtracting decibels: the antenna's gain minus the intensity of the radiation in the back, in dB.

The horizontal plane plots make this even easier. The front-to-back ratio can be simply read from the circular scale nearest to the rear lobe of the radiation pattern. For example, looking at the three-element Yagi at a half wavelength height over the ground shown on the right of Figure 15-xx on page 245, it can be seen that the intensity of the rear lobe radiation is about −23 dB. That means it is 23 dB weaker than the intensity from the front, which is labelled as 0 dB on these plots. The front-to-back ratio of this antenna is about 23 dB.

This is a good front-to-back ratio for a three-element Yagi. It represents almost 4 S meter units of difference. It will be useful while listening, by strongly attenuating signals from directions of no interest, and when transmitting, by focusing the power of the signal in that direction.

307 Each additional director, up to about 12, adds about 1 dBi of gain on HF. Commercially available UHF Yagis exist with as many as 70 small elements and gain over 23 dBi. One of the largest Yagis constructed in Ireland was a 43-element, 30 m long antenna operated on the 2 m band for an IRTS Brendan Award attempt in 2014. The elements were supported by ropes. Its gain was 26 dBi. When fed with 750 W it generated a main lobe beam equivalent to a 150 kW isotropic antenna.

308 Yagis with straight elements have deep nulls at the sides (90°) because each element has a null in those directions. The nulls at the sides are likely to be deeper than those to the rear.

309 Not to be confused with the *front-to-rear* ratio, which compares intensity in the front to a 180° average of the entire rear.

15.17 Capture Area (Effective Aperture)

In the far radiating field, a receiving antenna captures only a small amount of the energy radiated by a remote transmitter. That energy comes from the portion of the propagating electromagnetic wave that is sufficiently near the receiving antenna.

The received power available at the terminals of the antenna depends on the CAPTURE AREA, also called the EFFECTIVE APERTURE of the antenna.

For dish antennas, the capture area is very easy to see. It is almost identical to the frontal area of the dish itself. For wire antenna such as Yagis, the capture area is normally larger than the physical shape of the antenna. Its shape is determined by the type of the antenna. For a Yagi, and similar to a half-wave dipole, it is roughly elliptical as shown in Figure 15-xxiii. Generally, the bigger the antenna, the larger the capture area, and the larger its gain.

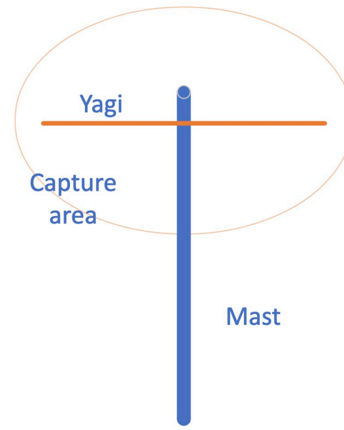


Figure 15-xxiii: Capture area (effective aperture). [EI9ILB]

Capture area is an important characteristic of UHF parabolic and horn antennas.

15.18 Parabolic Antenna

PARABOLIC ANTENNAS are mainly used at UHF and microwave frequencies. Their key application is space communications. An example of such an antenna, used for geostationary satellite signal reception, is shown in Figure 15-xxiv.

When used for transmitting purposes, they require specialised feed systems, such as waveguides, see section 14.7.

An antenna located at the focal point of a parabolic reflector, or dish, can provide considerable gain with a large capture area.

Figure 15-xxiv: Parabolic antenna. [Image by Petr Kratochvil, see page 375]

A 1.2 m diameter parabolic DISH operated on 432 MHz, which is the frequency of the 70 cm band, provides about 10 dBd, or 12 dBi gain, i.e., almost a 100 times stronger radiation in front of the dish than from a half-wave dipole in free space.

The beam width of the signal will be very narrow if the design focuses the transmitted energy at the focal point of the dish. Make sure to research parabolic antenna design and safety considerations.

- ! Never stand directly in front of an active parabolic antenna, and do not point it at people or animals.
- ! Exercise caution especially with small dishes, because they concentrate the available energy far more than a larger dish does.
- ! Exercise caution when operating at microwave frequencies, or with a power amplifier.
- ! Be careful near the feed point, where the EMF can be *very* intense.

15.19 Horn Antenna

Horn antennas are used at microwave frequencies. They can be regarded as flared out or opened out waveguides.

They produce a large effective aperture (capture area) than that of the waveguide itself which gives them directivity and gain.

They are highly directional, focusing their beam in front of the flared opening.

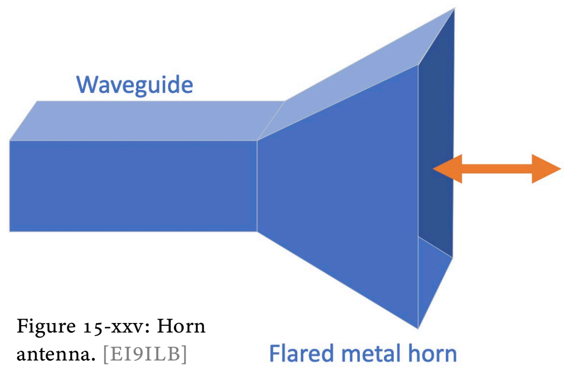


Figure 15-xxv: Horn antenna. [EI9ILB]

- ! Never stand directly in front of an active horn antenna, and do not point it at people or animals.
- ! Just as with parabolic antennas, beware of potentially intense near fields to the sides of the horn.
- ! Be very careful close to the feed point, and never look inside an active horn or an active wave guide.

15.20 Effective Power: EIRP and ERP

The effective isotropic radiated power (EIRP) and the effective radiated power (ERP) are also referred to as the Equivalent Isotropic Radiated Power, and the Equivalent Radiated Power. They inform us about the ability of an antenna to focus power in its best direction. They also account for the different components of the station and their cumulative effect on the power delivered to the antenna.

The EIRP and ERP are used in relation to the maximum radiation direction of an antenna. As discussed earlier in this chapter, this maximum direction would be in front of a parabolic or a horn antenna, or slightly above the horizon and in front of a Yagi, or simply in front of, or directly behind a half-wave dipole.

The only difference between EIRP and ERP is in the type of an antenna they refer to. EIRP uses an isotropic antenna, which has no gain or directivity. ERP uses a half-wave dipole in *free space*, which has a gain of 2.15 dBi over an isotropic antenna, see 15.15 Directivity, Efficiency, and Gain. Because of this, EIRP and ERP are used for slightly different purposes, but they can be easily converted to each other.

The EIRP is generally more informative because it can be directly used to calculate field strengths that are to be expected in front of an antenna in the far radiating field. It can also give an idea of what would be the signal strength at the receiving station. ERP, which references a half-wave dipole in free space, is similar, but by referencing a dipole may feel more familiar to radio amateurs.

The Irish regulations generally specify power limits as PEP measured at the output of the transmitter or the final amplifier, with the exception of some bands, like the 60 m band, which have power limits expressed as EIRP. See Table 25-C: Operational bands: edges, status, power, restrictions.

15.20.1 Calculating EIRP and ERP

Please review section 9.4 Effective Power that discusses decibels before proceeding. To calculate the EIRP or the ERP of a station you will need to know:

- the output power of the transmitter
- the dB increases of power provided by any amplifiers
- the dB decreases of power due to line losses and any other devices
- the gain of the antenna.

For example, let's find out the effective powers of a transmitter that outputs 100 W into an amplifier that has a gain of 4 dB, a coaxial cable that has a loss of 1.15 dB, and an antenna that has a gain of 5 dBd or 7.15 dBi.[310] First of all, find the dBW value of 100 W from Table 9-B on page 118:

$$100\text{ W} = 20\text{ dBW}$$

Then, to calculate EIRP, add all the increases and decreases together, using dBi:

$$\text{EIRP} = 20\text{ dBW} + 4\text{ dB} - 1.15\text{ dB} + 7.15\text{ dBi} = 30\text{ dBW}$$

and finally, if you wish, convert the result in dBW back to W using Table 9-B:

$$\text{EIRP} = 30\text{ dBW} = 1000\text{ W}$$

To calculate ERP, use dBd instead of dBi. In this case, the antenna gain is 5 dBd:

$$\text{ERP} = 20\text{ dBW} + 4\text{ dB} - 1.15\text{ dB} + 5\text{ dBd} = 27.85\text{ dBW}$$

27.85 dBW is about 600 W.[311] You are not required, however, to be able to convert such value of dBW to W at the exam. You only need to know the values in Table 9-B.

Let's consider the practical meaning of those results.

310 Recall that $dBi = dBd + 2.15$ because the half-wave dipole in free space has a gain of 2.15 dBi.
311 To convert EIRP to ERP you can subtract 2.15 dB from EIRP. $ERP = EIRP - 2.15\ dB = 30\ dBW - 2.15\ dB = 27.85\ dBW = 600\ W$

15.20.1.1 *What is the practical meaning of the EIRP result?*

The EIRP of 30 dBW, or 1000 W, tells us that the power radiated in the strongest direction of the station's antenna is equivalent to what 1 kW fed to an isotropic antenna would deliver if it were used instead of our entire station.

Part of the reason for this considerable amount of radiated power in our example case is the amplifier, which has increased the 100 W transmitter output by 4 dB to about 250 W. Some of it, 1.15 dB, was then lost to heat in the transmission line, costing us about 60 W. However, the antenna, with its considerable gain of 7.15 dBi has focused the remaining 190 W of power, just like a torchlight focuses the light from its lightbulb, into an intense beam. To get the same intensity of the beam by using the theoretical isotropic antenna we would have to feed it 1 kW of power.

Of course, the isotropic antenna would radiate that energy in all directions, while our antenna only radiates in a tightly focused area, and very little if anything in other directions. That is the reason why we do not need to feed it as much as 1 kW.

It is important not to misread that figure. The power radiated by the antenna is not 1 kW. It could not be more than 190 W that was fed to the antenna. No more power can be radiated than is being supplied. However, the 190 W is focused on the direction of interest, and there is little power radiating in other directions.

EIRP can tell us something about the strength of the signal that a receiving station is likely to hear, if it is located exactly in the antenna's best direction, and if we ignore all other losses and the vagaries of propagation.

15.20.1.2 *What is the practical meaning of the ERP result?*

The ERP of about 600 W tells us something a little different. It shows us the power we would need to feed into a half-wave dipole (in free space) to produce the same field strength as our antenna does in its strongest direction. Naturally, the half-wave dipole would need be oriented to match our antenna's strongest direction.

It does not mean that the antenna is radiating 600 W of power in any direction. It cannot radiate more than was fed to it, 190 W in our case. However, it is performing in the direction of interest just like the reference dipole would if that dipole was supplied 600 W. Our antenna is clearly better than that dipole, in the direction of interest, by requiring only 190 and not 600 W. The dipole may be better, on the other hand, in other directions, where our antenna, without any doubt, performs worse than the dipole.

Some radio amateurs prefer to compare power levels thinking of dipoles, rather than absolute levels of power. ERP is more suitable for those needs.

Bear in mind that ERP refers to a half-wave dipole in free space, rather than a more realistic dipole installed at a normal height above the ground, which has an even larger gain, see footnote 306 on page 247. As a result, using the ERP to intuitively compare the output of this station to a dipole may not be as practical as using EIRP.

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16 Propagation

FOUR EXAM QUESTIONS · SECTION A7

Radio waves, once generated by an antenna, travel away from it to reach even the furthest places – this is PROPAGATION. It is the very essence of radio. Without it, there would be no radio communication. As soon as you start making contacts, especially those further afield, you will discover how interesting and sometimes surprisingly unpredictable propagation can be. Many of its aspects are not yet fully understood by the science, and radio amateurs are at the forefront of making discoveries. Keep learning about propagation to increase your chances for successful, long-distance contacts.[312] This chapter introduces the key principles of propagation.

16.1 Electromagnetic Wave

See Chapter 7 Radio Waves and Spectrum, to review what is an electromagnetic wave, its electric and magnetic fields, speed at which they travel, and polarisation. Please also see section 5.1.3 Wavelength and Frequency to review the relationship between the wavelength, its period, and its frequency.

Propagation of radio signals is possible because of the way electromagnetic waves travel, i.e., PROPAGATE, entirely on their own, once emitted by the transmitting antenna.

16.1.1 Propagation Velocity

In the vacuum of free space, away from the ground, any objects, and any sources of EMF, electromagnetic waves propagate at the highest possible speed of anything: the SPEED OF LIGHT, approximately 300 000 km/s.

Light is a very high frequency electromagnetic wave, see the spectrum diagram shown on page 84. Radio waves are just like light, except they are invisible, can pass through objects, have a lower frequency, and a longer wavelength than light. Radio waves travel almost as fast in the air as in vacuum. However, their PROPAGATION VELOCITY is a little slower when they travel through other media, such as water, gases, objects, etc.

Radio waves are slowest when they travel as AC through transmission lines, where they can be slowed down to as little as 65% of the speed of light, see 14.3 Velocity Factor.

312 Many publications discuss propagation. A notable work is *Low-Band DXing* by John Devoldere ON4UN. See also the *ARRL Handbook,* and the *RSGB Radio Communications Handbook.*

16.2 Cycles and Solar Phenomena

The radiation from the Sun is responsible for the creation and the destruction of the various layers in the atmosphere that enable propagation of radio signals. Those layers are discussed later in this chapter. Because the Sun's activity changes all the time, propagation will also vary, from hour to hour, day to day, and from year to year.

16.2.1 Daily Cycle

When the Sun illuminates the atmosphere on the day side of Earth, the Sun's electromagnetic waves, primarily UV (ultraviolet) radiation, ionises gases contained in the atmosphere.[313] The ionisation changes the gases, so they become electrically active. In their ionised state, they can refract and reflect radio waves, or absorb them, depending on their altitude and the level of energy that they have received from the Sun. The Sun's UV radiation continues to re-ionise them during the day, especially when it is strongest, at noon during the summer, when the Sun is at its highest angle above the horizon. However, the ionised gases quickly revert to their electrically inert state when the supply of UV diminishes as the Sun sets. During the night, some of the ionised layers disappear, whilst others thin out and move to a higher altitude. Radio propagation is very different during the night and the day.

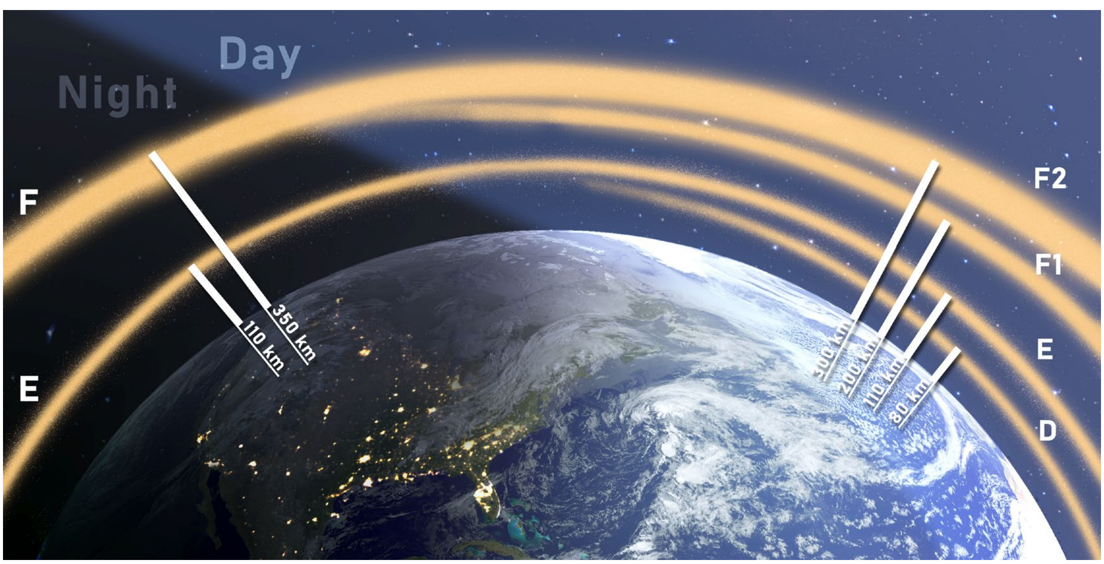

Figure 16-i: Daily cycle of ionospheric layers. [Image by Konrad Atanaziewicz, see page 375]

Figure 16-i shows the daily cycle of those ionised layers of the atmosphere which greatly influence radio signal propagation. They are discussed in section 16.3.3 Ionospheric Layers.

313 Ionisation that is of interest to radio propagation affects oxygen in all the atmospheric layers of interest, and nitrogen and nitric oxide in the lowest layers.

16.2.1.1 *Grey Line*

During the short period when the night turns into the day, and the other way round, several interesting changes occur. During the sunrise, some layers thicken faster than others. This is illustrated in Figure 16-i, where on the sunrise side of the grey line the D layer has not yet formed, but the F layers have started to form and thicken. During the sunset, while some of the layers remain, others disappear more quickly.

This period of a transition between the day and the night is known as the GREY LINE. MF and HF propagation, particularly on the lower frequencies, can be very successful during the grey line, especially between two points that are on either side of Earth but within the grey line. The exact mechanisms of grey line propagation are still not fully understood, and several theories have been proposed.

You can see Ireland at sunrise on the grey line map in Figure 16-ii. This could be a good time to attempt some very long-distance contacts to other regions which are also on their grey line.

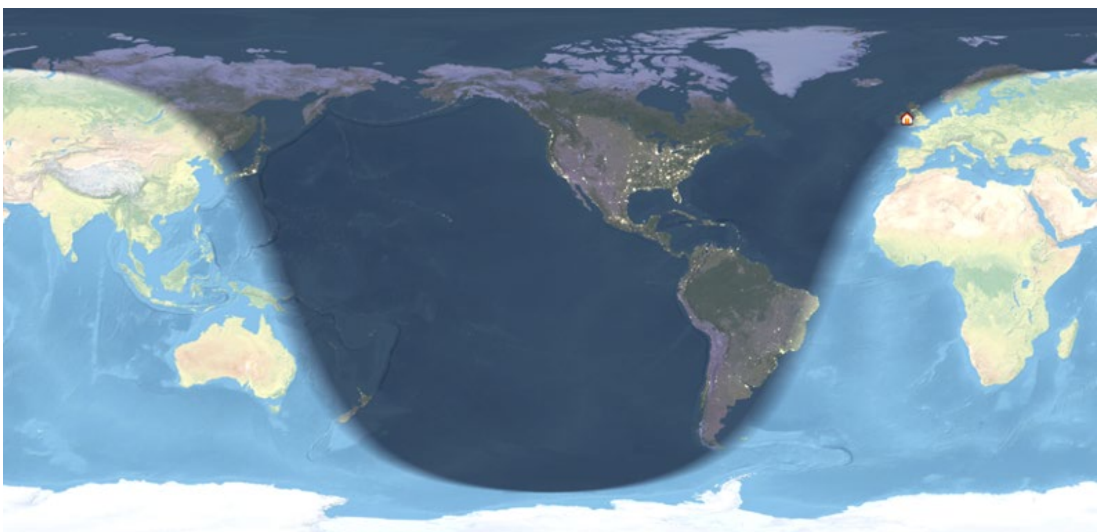

Figure 16-ii: Grey line. Ireland is at sunrise, 08:00 in November. Notice that both New Zealand and Japan are also on the grey line. Map produced by G4ELI application g4eli.com/world-map [EI6LA]

16.2.2 Solar Cycle

The Sun follows an approximately 11-year activity SOLAR CYCLE during which it becomes very active, reaching the SOLAR MAXIMUM, and then, 5½ years later, becomes somewhat inactive again, reaching the SOLAR MINIMUM.[314]

Electromagnetic radiation from the Sun peaks during the solar maximum, increasing the overall levels of ionisation of the earth's atmosphere, and greatly

314 At the time of writing, Jan 2024, *solar cycle 25* is in progress. By the current estimates, the next solar maximum is expected between 2024–2025, after which the Sun will decrease its activity, with this cycle expected to end around 2030. See also en.wikipedia.org/wiki/Solar_cycle.

enhancing propagation of radio waves. Conversely, during a solar minimum, propagation is more restrained, especially on the higher HF bands. Some of the amateur bands, like the 10 and 12 m bands, may remain unusable, because of insufficient ionisation.

16.2.3 Sunspots and Flares

The surface of the Sun is frequently disturbed by strong magnetic forces deep within it. This manifests itself in SUNSPOTS, from which the Sun emits strong electromagnetic waves. There are more sunspots during the solar maxima. Solar observatories count the number of individual sunspots and groups of sunspots every day and calculate the SUNSPOT NUMBER that represents the daily totals.[315] A high sunspot number indicates an active Sun, which yields stronger ionisation and, usually, better propagation.

The amount of electromagnetic radiation emitted by the Sun that falls on Earth is measured as the SOLAR FLUX. A high solar flux also indicates an active Sun. However, a very high number, associated with more intense radiation, may cause disturbance to Earth's magnetic field, increasing noise that can be heard on the radio.

When a sunspot is particularly large or active, a SOLAR FLARE may occur. The Sun emits particularly strong electromagnetic radiation during a solar flare, including intense X-rays, which cause strong ionisation. This radiation is travelling at the speed of light, and it reaches Earth within minutes of being emitted by the Sun.

The Sun's surface rotates. The sunspots rotate with it, taking approximately 27 days to complete a FULL ROTATION.[316] If a strong flare emitted from a sunspot is causing issues or good propagation, similar conditions are likely to occur 27 days later, unless the sunspot's activity subsides in the meantime.

16.2.4 Geomagnetic Storms and Auroras

If a strong solar flare is directed at Earth, its radiation will ionise layers above northern or southern latitudes, while also interacting with Earth's magnetic field. When that happens, AURORA may be visible. In the northern hemisphere it is called *aurora borealis* or NORTHERN LIGHTS, and *aurora australis,* SOUTHERN LIGHTS, in the Earth's southern hemisphere.[317] Figure 16-iii shows a spectacular example. Aurora affects propagation, both aiding and impeding it, or by bending the paths along which signals travel around the planet. It can be also used directly for VHF propagation, see 16.8.6 Auroral Reflection and Scattering.

315 A large sunspot number indicates there are more sunspots grouped into clusters than individual ones spread apart. It is not a direct count of each one. See en.wikipedia.org/wiki/Wolf_number.

316 The visible surface of the Sun, the *photosphere,* consists of *plasma,* which behaves like a fluid rotating at different speeds at different latitudes. It takes 25 days at the equator and 35 days at the poles. The region where sunspots occur takes 26 days to rotate, however, Earth's own rotation adds one day, making the same sunspot take about 27 days to come back to its original, Earth-facing position.

317 Predictions of aurora visibility from the UK and Ireland can be found at aurorawatch.lancs.ac.uk and from www.swpc.noaa.gov

Figure 16-iii: Aurora Borealis, Northern Lights, seen over Alaska.
[Image by NASA. See page 375]

The solar flare can also cause Earth's magnetic field to become unstable, increasing the noise on the radio bands. A particularly strong solar flare can be accompanied by a CORONAL MASS EJECTION (CME), although that can occur on its own, too. When it happens, the Sun not only emits strong and disturbed electromagnetic waves, that reach Earth within minutes, but it also ejects high energy particles. They take longer to arrive at Earth than the electromagnetic radiation, taking a few days rather than just a few minutes.[318] When the ejected particles reach our planet, they cause a deep disturbance to Earth's magnetic field, known as a GEOMAGNETIC STORM.[319] A partial or a complete RADIO BLACKOUT may occur, during which radio communication becomes temporarily impossible. When the storm passes, the ionisation tends to remain strong, potentially improving propagation once the noise levels drop.

There are significantly more solar flares, coronal mass ejections, and geomagnetic storms during a solar maximum than when the Sun is quiet, at its solar minimum.

318 Highly energetic electrons and protons ejected during a coronal mass ejection, or a CME, can take as little as 13 hours and as long as 86 days to reach the Earth. On average, 3.5 days. Because electromagnetic radiation from a CME arrives at the speed of light, within 8 minutes, solar observations can predict extreme events. Rare, intense CMEs cause strong electromagnetic pulses that affect radio and electrical installations. Electrical networks were disabled in North America on 9 March 1989. The *Carrington Event* on 1–2 Sept 1859 caused auroras during the day. Pylons sparked. Fires erupted in telegraph stations. Current solar activity predictions are at www.swpc.noaa.gov.

319 Amateur radio propagation bulletins often include the *Kp Planetary Index,* a number between 0–9. It describes how much the Earth's magnetic field is disturbed. When it is over 4, it indicates a geomagnetic storm, increasing noise levels, and making auroras more likely. See www.hamqsl.com

16.3 Atmosphere

The Earth's atmosphere consists of many regions layered atop each other. Two of those regions are of particular importance to radio propagation: the troposphere, which is the lowest layer of the atmosphere, and the ionosphere, which is part of the thermosphere, the second highest atmospheric layer.

16.3.1 Troposphere

The TROPOSPHERE is the lowest layer of the atmosphere. It extends from the surface of Earth to the altitude of about 10 km above it. Because it contains most of the atmospheric water vapour, it is responsible for most weather phenomena. Troposphere influences VHF and UHF propagation, because of the water vapour which it contains, and to which those frequency bands are sensitive.

16.3.2 Ionosphere

The IONOSPHERE plays the most important role in the propagation of HF and lower frequencies. Ionosphere is a region located at altitudes of 50–1 000 km above the earth. It contains several ionospheric layers, some of which directly determine the ability to communicate using radio.

16.3.3 Ionospheric Layers

The four IONOSPHERIC LAYERS that are important to radio wave propagation are shown in Figure 16-iv. The most important layers of the ionosphere are the D, E, and the F layers.

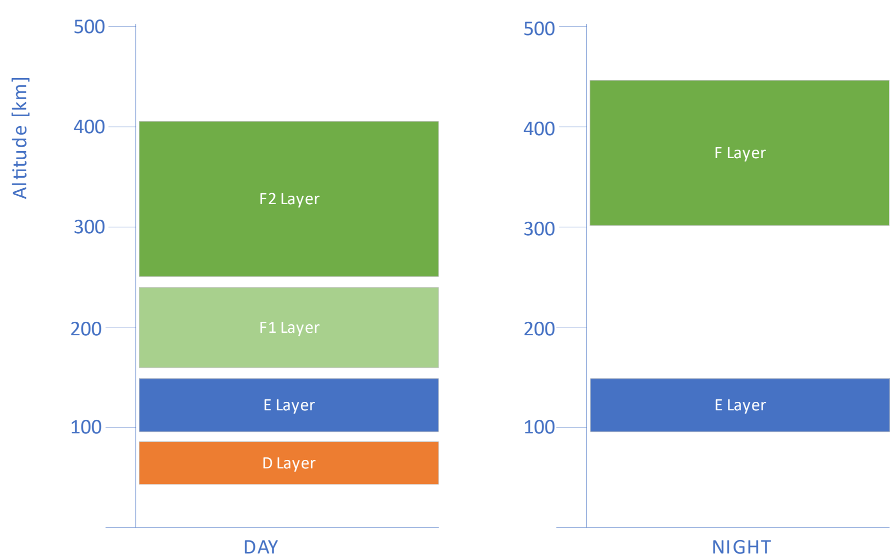

Figure 16-iv: Layers of the ionosphere important to radio propagation. [EI9ILB]

As discussed earlier, the layers undergo a cycle of change every day. Radiation of the Sun replenishes them during the day, and they diminish during the night. Figure 16-i on page 255 shows the gradual transition between the night and the day.

16.3.3.1 *D Layer*

The D LAYER exists only during the day while the Sun ionises the lower layers of the ionosphere. It quickly disappears at sunset. Its altitude is about 50–90 km. The D layer absorbs LF and MF radio waves, preventing their use for long distance (DX) daytime communication. Ground wave propagation, however, still allows MF to be used for local communication during the day, see 16.5.1.

HF is less affected by the D layer than LF and MF. Long distance communication remains possible during the day, especially on the higher HF bands during the solar maximum.

16.3.3.2 *E Layer*

The E LAYER exists during the day and the night, at between 90–150 km above the earth. It is thicker during the day. The E layer both contributes to and prevents some forms of propagation.[320]

The main positive contribution of the E layer is when irregular, thicker E layer clouds, known as SPORADIC E, form during the May–July[321] mornings and just prior to noon. Sporadic E makes VHF long-distance propagation possible, even as far as 2500 km. It is, however, unpredictable and does not last long.

16.3.3.3 *F Layers*

The F LAYERS play the most important role in HF propagation. During the night there is a single F layer at approximately 300–450 km altitude. During the day, the F layer splits into F1, at approximately 150–250 km, and F2 at 250–400 km.

The F1 layer generally does not affect propagation, except during the summers of a solar maximum, when it helps HF travel similar distances to those offered by the F2 layer.

The F layer during the night, and the F2 layer during the day, strongly REFRACT (bend) radio waves, causing them to turn around and return to Earth. This effect looks just as if the radio waves were being REFLECTED from the F layer.

The shallower the angle at which the radio waves hit the F layer, and the higher the layer, the longer distance will the refracted radio wave reach. A SINGLE HOP against the F layer can be as far as 4000 km.

320 The E layer is believed to be responsible for *ducting* of HF along great distances. Ducting, in this context, means reflections of HF radio waves between the F and the E layers, without having to reflect from the surface of the earth, and so, without being attenuated as much.

321 In the northern hemisphere.

16.3.3.4 *Multi-hop Propagation*

If the radio wave subsequently reflects from the Earth's surface, especially from the salty water of an ocean during its night, it can travel back to the F layer for another reflection, and so, another hop. MULTI-HOP propagation allows HF to reach any point on Earth unless the radio wave has been absorbed along its way.
The longest possible multi-hop propagation happens on the night side of the planet because there is no D layer absorption, unlike on its day side. It can be particularly successful between two points located on either side of the planet in their grey line, see 16.2.1.1.

Ionospheric propagation is a complex phenomenon, with many contributing factors. Much of it is still being studied. Unusual, long distance propagation paths are possible from time to time. Without doubt, you will experience those surprises.

16.4 LINE-OF-SIGHT PROPAGATION AND RADIO HORIZON

If the two stations could see each other, radio communication is possible on all the bands. This is known as the LINE-OF-SIGHT propagation.

Because radio waves can pass through some solid objects, clear view is not necessary. However, if ground, hills, mountains, or a body of water, are in the way, they will prevent line-of-sight propagation. Similarly, large structures containing metal, including reinforced concrete, may prevent line-of-sight communication, depending on their construction.

In general, if the other station is above the visible horizon, communication should be possible. For those reasons, the limit of the line-of-sight for radio communication is also known as the RADIO HORIZON.

Height (elevation) helps greatly. A station on top of a hill will have a longer line-of-sight. Its radio horizon will be further than for a station at the foot of the hill or in a valley.[322]

Line-of-sight propagation benefits from a matching polarisation of the radio waves, see 15.6. It means that when relying on line-of-sight propagation the orientation of the transmitting antenna, vertical or horizontal, should match the orientation of the receiving antenna.

16.4.1 Free Space Attenuation

Radio waves radiate from the antenna and reach everywhere within the line-of-sight, although some directions may be stronger for antennas that have directivity, such as a Yagi. As they travel, radio waves attenuate, i.e., they become weaker, because the wave spreads over an ever-increasing amount of space.

322 For an antenna at 20 m above the ground the line-of-sight distance is just over 18 km. If the station is on a hill 500 m high, the line-of-sight distances increases to over 90 km. The formula for approximate line-of-sight distance d in kilometres is: $d = \sqrt{17h}$, where h is the elevation of in metres.

The FREE SPACE ATTENUATION of the signal describes the amount the signal weakens as it travels in free space, i.e., in vacuum, well away from the ground and other electromagnetic influence, including other EMF sources. However, the amount of free space attenuation is very close to actual signal attenuation in the air. On the other hand, signals travelling in conductors, or through water, water vapour, or ionised gases, will attenuate more than in free space or air, losing their energy to heat and other processes.

Once the radio wave is travelling in the antenna's far radiating field, see 15.2 Near and Far Antenna Fields, its power drops according to a simple rule known as free space attenuation.

- The free space attenuation of a signal reduces its power with the square of the distance travelled. In other words, as the distance from the antenna doubles, the power of the signal is only a *quarter* of what it was at the antenna.[323]
- The free space attenuation can be expressed in terms of signal voltage, but unlike with signal power, as the distance doubles, the voltage only *halves.*[324]

Despite free space attenuation, sufficiently strong signals can be easily detectable tens of thousands of kilometres away. Your radio signals could be heard on the Moon, other planets, and indeed, anywhere in the universe.[325]

16.5 LF, MF, and HF Propagation Mechanism

While line-of-sight propagation works on all bands, including VHF, and UHF, there are some mechanisms that work mainly on LF, MF, and HF.

16.5.1 Ground Wave

The ground wave propagation is somewhat unique to LF and MF. Signals on those bands are able to follow the curvature of the ground, especially when wet, water, especially salty water, even climbing and descending small hills, however, not tall mountains. A GROUND WAVE allows signals to travel just beyond 200 km, which is further than line-of-sight, but nowhere near the distances achieved by refraction from ionised layers.

The ground wave is the main reason why the 80 m band remains usable for local communication during the day, such as the IRTS 12:00 (local noon) Sunday news

323 This is *inverse square law*. It is common is physics. As one quantity *doubles,* such as the distance, the other one, such as signal power, behaves *inversely,* that is, it shrinks, at *square* of the increase of the first one. In other words, it shrinks as fast as the distance multiplied by distance. For a doubling of the distance, $2 \times 2 = 4$, power reduces 4 times as fast, i.e., to ¼, a quarter, of what it was. See also footnote 30 for more information about *squares* and the *inverse square law.*

324 Recall that power $P = V^2/Z$ where Z is impedance in Ω. It stems from Ohm's law and the fixed impedance of free space, $Z_0 = 377\ \Omega$. This only applies in the far field of the antenna.

325 With *good propagation,* despite ionospheric and ground reflection losses, a 5 W signal transmitted on HF in Ireland will be heard as far as Australia.

service on 3.650 MHz. The news service can be heard in Ireland, but not much beyond the island, especially during the solar minimum.

16.5.2 Sky Wave

SKY WAVE propagation is the name of the propagation mechanism which uses the ionised ionospheric layers discussed in 16.3.3 to REFRACT, and therefore, to REFLECT the radio waves travelling from the antenna.[326] The shallower the angle of the radiation from the antenna, and the higher the ionospheric layer, especially the F and F2 layers, the further the sky wave will reach around Earth's surface. However, to refract from the F layers, the wave must also pass through the absorbent D and E layers. Very shallow angles are excellent for refraction, but they mean the wave must travel through a much thicker absorbent layers, therefore, there is a limit to how shallow the angle can be during the day, when the D layer is present.

When radio waves refract from the ionospheric layers, they lose their original polarisation. This is the reason why it is no longer beneficial to match the orientation, vertical or horizontal, of the transmitting and the receiving antennas.

16.6 LF and MF Propagation

The sky wave propagation, together with the line-of-sight, and the ground wave propagation mechanisms mean that LF and MF signals can travel very far around Earth. Figure 16-v on the next page shows all the different mechanisms together.

326 Ionospheric refraction causes bending of the path of the radio waves. If sufficient, it will appear to a ground observer as if it were a reflection. On the other hand, radio waves tend to reflect from the surface of an ocean, or from the ground, with little bending – closer to what is meant by reflection than by refraction. The two terms are used interchangeably when talking about propagation.

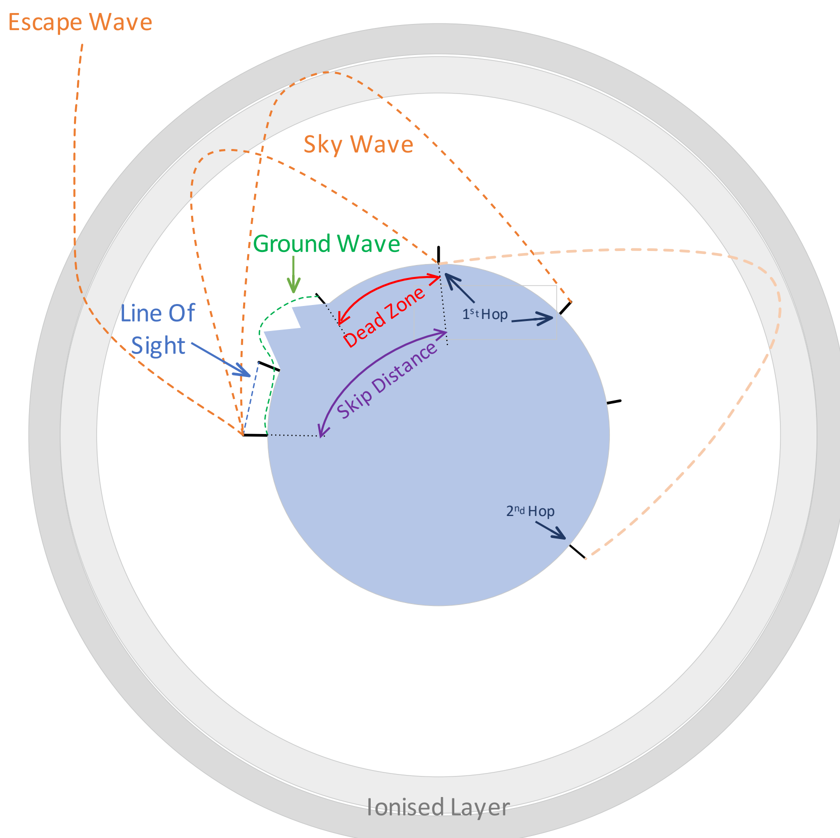

Figure 16-v: LF and MF propagation. With good propagation, further hops of the sky wave are possible, possibly reaching all around the planet. [EI9ILB]

The SKIP DISTANCE is the distance from the transmitting antenna to the closest place on the planet that can be reached by a sky wave travelling from the antenna at angle that is neither too steep nor too shallow. Signals travelling vertically, or at steep angles, may not refract enough in the ionised layers to reflect. They will refract (bend) a little, but they will not return to Earth, leaving the planet. This is known as the ESCAPE WAVE. There will be, however, a region, beyond the reaches of line-of-sight and ground wave propagation, but which is not yet as far as the skip distance, where radio communication is not possible on a given LF or MF frequency using that antenna. That region is known as the DEAD ZONE. It is not fixed. It will keep changing because the propagation conditions, including the height, thickness, and the level of layer ionisation, do not remain the same.[327]

If there are no magnetic disturbances such as a geomagnetic storm, and if the ionisation is strong enough, a second and even further hops will take place, especially if

327 It may be possible for two relatively close stations, one seemingly in the dead zone of another, to be able to communicate through a sky wave reflecting from a third point that is common to both, but far away, perhaps on a highly radio-reflective surface of a salty ocean. This is known as *backscatter*.

reflecting from a salty ocean, making global communication possible. Because radio waves travel in all directions, they can reach the destination by hopping along the most direct, SHORT PATH, or take a LONG PATH, travelling around the world in what seems like the opposite way. When that happens, signals from the east come from the westerly directions etc. Long path is more likely with good ionisation and is influenced by the position of night and day along its way, which may be diminishing the short but not the long path, depending on the band in use. Sometimes, signals will arrive via both paths, creating an echo-like effect.

16.7 HF Propagation

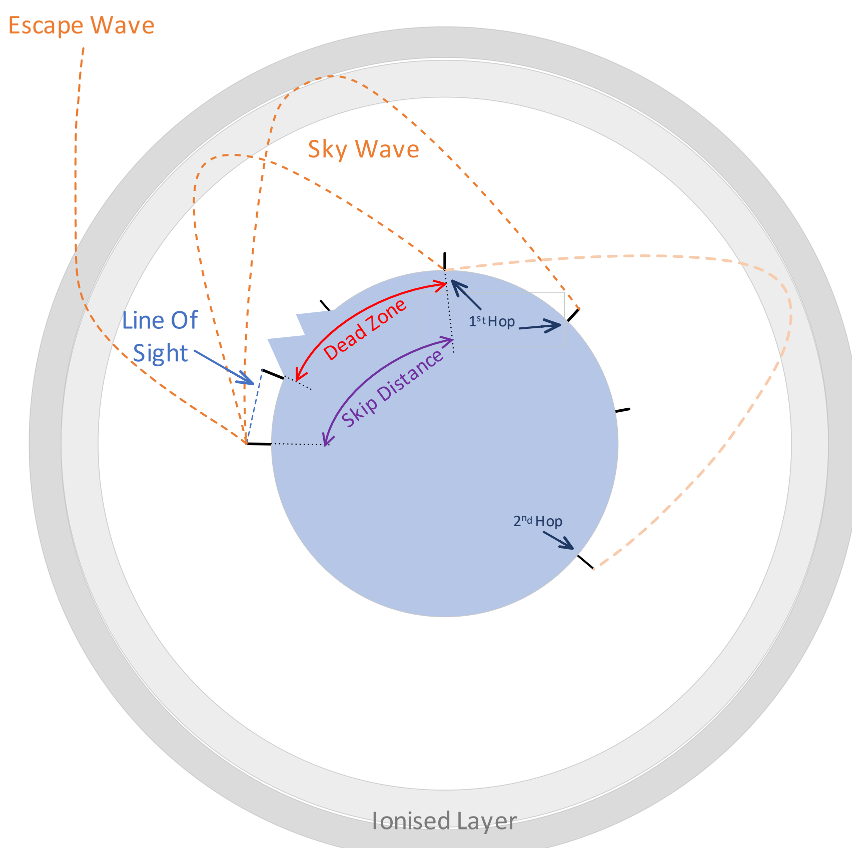

Figure 16-vi: HF propagation. Further hops of the sky wave are likely in good conditions. [EI9ILB]

Like MF and LF propagation, HF propagation uses several mechanisms, including sky wave and line-of-sight propagation. However, HF does not benefit from ground wave propagation. As shown in Figure 16-vi, the main difference between HF and MF/LF propagation is that the dead zone extends from the limit of line-of-sight, i.e., the radio horizon, to the closest place on the planet that can be reached by a single hop of the sky wave. The meaning of the skip distance and the escape wave, as well

as the concept of multi-hop propagation are identical to those discussed in the previous section.

16.8 VHF and UHF Propagation Mechanisms

The main propagation mechanism for VHF and UHF is line-of-sight, already discussed in 16.4. Because this distance is rather short and affected by obstacles, a network of REPEATERS is frequently used to extend the practical VHF and UHF communication range. Repeaters are stations that receive and then send signals on predefined frequencies. They are usually installed on prominent hills, benefitting from longer line-of-sight distances that high elevations make possible. Such locations also allow the retransmitted signals to reach areas on the other side of the hill or a mountain, connecting stations that cannot directly see each other.

However, there are other, interesting propagation mechanisms that are somewhat unique to the higher frequencies of VHF and UHF.

16.8.1 Tropospheric (Space) Wave

The TROPOSPHERIC WAVE, also known as the SPACE WAVE – please note, not sky wave – extends line-of-sight propagation by approximately 15% thanks to the refraction of VHF and UHF in the water vapour (humidity) of the troposphere. It has the effect of slightly bending the electromagnetic wave towards the ground.

Thanks to it, it is possible to use VHF/UHF to reach stations which are slightly beyond the visible horizon, up to about 1.15 of the distance from the antenna to the horizon in a visual line-of-sight.

16.8.2 Troposcatter

If the tropospheric layers of humid air are graduated, which can happen at times of changing, uneven temperatures, a TROPOSPHERIC SCATTERING, also known as the TROPOSCATTER allows for longer propagation paths beyond the horizon. Depending on the weather conditions, distances as long as 100–500 km are possible.

This phenomenon is caused by the scattering of VHF and UHF radio waves in a manner similar to how visible light scatters in fog. Lights of a distant city can be seen over the horizon on a misty night, just like how the lights of a car illuminate and can even blind when driving in a dense fog.

16.8.3 Aircraft Scatter (Aircraft Reflection)

The forward scattering or reflection of radio waves from high-altitude aircraft can cover similar distances to troposcatter. Commercial flights at cruising altitudes can remain in line-of-sight of stations about 400 km away, making a potential range between two well situated stations up to about 800–900 km.

Although it happens somewhat randomly, the AIRCRAFT SCATTER can be very common, with signals at least as strong as troposcatter, and the two propagation

mechanisms can be confused. What differentiates them is that aircraft scatter does not rely on weather conditions, and that the favourable alignment of the aircraft along the path between two stations may only last for a few minutes.

16.8.4 Tropospheric Ducting

Normally, air gets colder the higher the altitude. Occasionally, the weather forms a phenomenon known as the TEMPERATURE INVERSION, and a layer of warmer air sits atop the colder. This creates a corridor of warm, moist air in the troposphere, that can persist for hours, sometimes longer. Such a corridor refracts VHF/UHF well, and it can propagate, or duct, radio signals well in excess of 1 000 km.[328] This propagation mechanism is known as the TROPOSPHERIC DUCTING.

16.8.5 Sporadic E

The ionospheric E layer fulfils many propagation roles. From time to time, dense, highly ionised clouds of the E layer form. This is most likely to happen in the morning till noon, May-August (northern hemisphere). When these SPORADIC E clouds form, VHF and UHF signals can propagate a very long distance by refracting from them. Distances of 2 500 km are possible.

This phenomenon is called sporadic because of its somewhat unpredictable and short-lasting nature.

16.8.6 Auroral Reflection and Scattering

When the aurora (northern and southern lights) is visible, it usually has a detrimental effect on the propagation of HF and lower frequencies. The associated unsettled geomagnetic conditions also increase the level of background noise. However, aurora can be beneficial to VHF and UHF. When it is visible, highly ionised layers form at higher geographic latitudes, especially at night. They can be used to propagate VHF/UHF a considerable distance, as much as 2 500–3 000 km. These phenomena are known as AURORAL REFLECTION and AURORAL SCATTERING.

16.8.7 Meteor Scatter

The METEOR SCATTER allows reflection of VHF/UHF from the ionised trails of meteors that pass through the atmosphere. Distances of 800 – 2 300 km are possible this way.

However, only very brief contacts are possible, from a few seconds to about a minute, because the trails decay very quickly. It is common to use dedicated digital modes, to make these brief contacts possible. The WSJT-X suite offers such modes. It

328 Records have been set using tropospheric ducting for contacts over 4000 km, especially at frequencies higher than VHF. Roger EI8KN made several 2 m VHF contacts between Ireland and Cape Verde, a distance of over 4200 km.

may not be known if a contact has taken place until after it is over, only once the software has finished processing the just-received data.

16.8.8 Earth-Moon-Earth (EME)

Strong signals and dedicated antennas can be used to direct VHF/UHF at the surface of the Moon, to reflect them back towards the Earth. This is known as the EARTH-MOON-EARTH (EME) propagation. If the sending and the receiving station can both see the Moon at the same time, very long distances, as much as half-way around the planet, 20 000 km, can be achieved.

Dedicated digital modes are used to make EME contacts easier, requiring significantly lower levels of power than in the past.[329] The WSJT-X suite offers modes suitable for EME.

EME is uniquely suited to the higher frequencies because the ionospheric layers that absorb HF and lower frequencies allow VHF and UHF to pass through and reach the Moon.

16.8.9 Satellites

It is possible to communicate using man-made amateur radio SATELLITES. They act like repeaters, using VHF and UHF, because those frequencies are less affected by the ionospheric layers, especially when using high orbit satellites. Distances depend greatly on the type of the satellite being used. Shorter distances are possible using low orbit satellites, and longer using geostationary ones.

There are over 40 satellites carrying amateur radio transponders in orbit at present, and many new planned to launch. Most are part of the Orbiting Satellite Carrying Amateur Radio (OSCAR) scheme. They can be used to transmit CW, phone, and data. This scheme is coordinated by Amateur Radio in Space (AMSAT) who support radio amateurs interested in space communications.[330] The IARU Region 1 Amateur Radio Space Exploration programme (ARSPEX), also offers good resources.[331] There is more on the Internet where you can learn about satellite amateur radio.[332]

Satellites are an interesting propagation mechanism, with its own technologies and a handful of additional regulations which ought to be studied. Importantly, every holder of an Irish CEPT Amateur Station Licence requires no further permits to point their antenna, even a small, hand-held Yagi, at the sky, and explore amateur radio in space.

329 The first EME contact between Ireland and the USA took place on 6 October 1987. Stations EI7M and W5UN exchanged messages using CW. A short video summarising that achievement is available at youtube.com/watch?v=3b2J0op5dMc

330 amsat.org

331 www.iaru-r1.org/about-us/committees-and-working-groups/arspex/amateur-satellites

332 en.wikipedia.org/wiki/Amateur_radio_satellite

16.9 Fading

The fluctuations of the received signal are called FADING. Fading can be fast, fluctuating signals every few seconds, or slow, making them go quiet and disappear, for half a minute or longer, before they strengthen and can be heard again.

Fading can be attributed to a variety of reasons. Propagation conditions tend to fluctuate all the time, affecting received signal strength. Signals arriving at the receiver by more than one path, also known as MULTIPATH, also due to the constantly changing nature of the ionised atmospheric layers, can either reinforce or cancel one another. Polarisation of the radio wave may be changed by propagation conditions resulting in an apparent reduction of strength. VHF and UHF are refracted by water vapour. Their fading may be also attributed to varying atmospheric conditions, especially the changing humidity and temperature.

It is common to refer to fading signals using its Q-Code QSB. See Chapter 26.

16.10 Estimating and Predicting Propagation

16.10.1 Critical Frequency

The CRITICAL FREQUENCY or VERTICAL INCIDENCE FREQUENCY is the highest frequency signal that will be reflected to Earth when beamed vertically upwards. It is measured several times a day from many locations around the world. The critical frequency is used to make several predictions and propagation forecasts, notably, it helps to predict the maximum usable frequency. Critical frequency values follow both the daily and the solar cycles, and they are highest during the solar maxima.

16.10.2 Maximum Usable Frequency (MUF)

The MAXIMUM USABLE FREQUENCY, MUF, for a defined pair of points on the planet, is the highest frequency at which reflection can take place from the ionised layers.

The MUF does not depend on the transmitter power or antenna gain. Instead, the MUF depends on the state of the ionisation and the angle at which the *sky wave* must travel from the transmitter to reach the receiver by means of a refraction from an ionospheric layer. Frequencies higher than the MUF will pass through the ionised layer and will not be reflected. They become escape waves.

The longest signal path for a particular layer is obtained when the sky wave leaves the Earth and approaches the layer at the lowest (most oblique) angle possible for reflection, without, however, being absorbed by a lower layer – see LUF in the next section.

The MUF can be estimated from the critical frequency. For a single hop refraction from the F2 layer, up to about 4000 km, the MUF is approximately three times the F2 critical frequency. For the E layer the MUF is approximately five times the E critical frequency.

16.10.2.1 *MUF Plots*

MUF plots are not part of the exam syllabus.

Figure 16-vii shows a map of world regions on 1900 UTC on 3 Nov 2022. Areas with a similar MUF share their colour. For each location, you can see the MUF that should allow a transmission from it to complete at least a single hop of about 3 000 km. Further distances may be possible, with multiple hops, if the locations of subsequent hop reflections also have a favourable MUF.

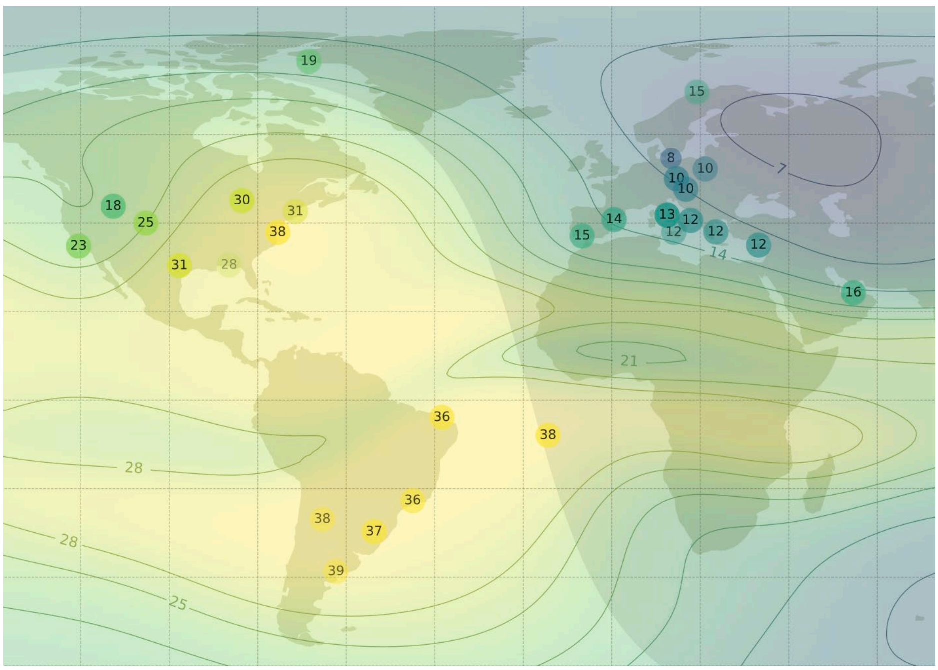

Figure 16-vii: MUF map showing maximum usable frequencies, in MHz, for a single-hop propagation from the given point up to 3000 km away. Evening, Nov 2022. Source: prop.kc2g.com [EI6LA]

Some areas of the world, highlighted in yellow, can succeed in transmitting to at least 3000 km away using frequencies as high as 39 MHz. All the HF bands, and even some VHF bands are open at those locations. On the other hand, Ireland, at the time when this plot was made, could not use any bands higher than 20 m (14 MHz) for such long-distance communication. In common terms, the 20 m band was *open* in Ireland, but the higher ones, like 15 m, were *closed.*

There are areas with an even lower MUF than in Ireland in this plot. Some parts of Northern Europe and Asia would not be able to use bands higher than 40 m (7 MHz) for long distance communications at that time on that day.

Overall, that was not a bad time and day for world-wide propagation. Although it would have been much easier to communicate across long distances using 15 m and 10 m bands, having usable 40 m and 20 m bands still permitted world-wide communications, albeit with a little more effort and noise.

When the Sun's activity is quiet, the 20 m band may remain closed, and even 40 m band may be unusable during the day. If that happens, only the lowest bands, 160 m, 80 m, and perhaps 60 m, may be available. Unfortunately, they do not usually work well or not at all during the day, and may be even poor after dark, due to ionospheric absorption of their frequencies.

MUF charts are updated regularly. The conditions change because of Earth's rotation causing the Sun to irradiate different parts of the planet, and any changes to Sun's activity. Compare to the plot taken one year later, nearer the solar cycle maximum, on 9 Nov 2023, just after the noon, in Figure 16-viii. Conditions in Ireland have improved greatly, with all HF bands open. Conditions in other parts of the world seem better that one year ago, too. Long-distance HF and even VHF is easier.

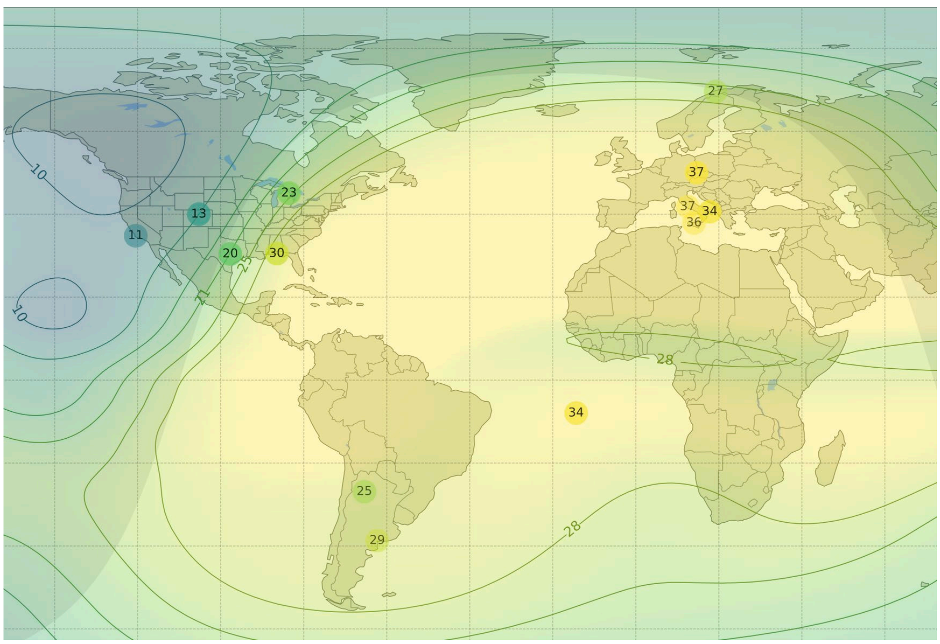

Figure 16-viii: MUF map showing maximum usable frequencies for a single 3 000 km hop, in MHz at noon, Nov 2023. Calculated and plotted using prop.kc2g.com [EI6LA]

16.10.3 Lowest Usable Frequency (LUF)

The LOWEST USABLE FREQUENCY, LUF, is the lowest frequency that can be used on a particular path, i.e., between any two specific points on Earth. The LUF depends on ionospheric absorption, mainly by the D and E layers, and on atmospheric (QRN) and man-made (QRM) noise. It is influenced by power and antenna gain.

Occasionally, the LUF can be higher than the MUF for a pair of stations. At such time there is no radio frequency that supports communication between them. There are online tools that predict when reliable communication may be possible.[333]

333 *Voice of America Coverage Analysis Program* www.voacap.com/hf, *Proppy* soundbytes.asia/proppy.

17 Measurements

TWO EXAM QUESTIONS · SECTION A8

Troubleshooting any radio related issues requires taking appropriate measurements. This short chapter introduces the basic principles and devices used for making the measurements which are useful when working with radio equipment.

! Electronic equipment can contain potentially lethal voltages or currents. Make sure you are familiar with safety procedures before making measurements. Please review section 19.3 Electricity and The Human Body.

17.1 Multimeter, Ammeter, Ohmmeter, Voltmeter

To review the basic electrical quantities, see section 3.2 Dimensions, Units, and Metric Prefixes. The most common measuring devices are:

- AMMETER measures current in amps A
- OHMMETER measures resistance in ohms Ω
- VOLTMETER measures voltage in volts V
- MULTIMETER, also known as the MULTIRANGE METER, measures current, resistance, and voltage. Some multimeters, like the one shown in Figure 17-i, can also measure other electronic phenomena, such as capacitance and AC frequency.

Figure 17-i: Multimeter (multirange meter). [EI6LA]

A modern meter offers a wide range of measurement ranges. For example, it may be able to measure voltage from as low as a microvolt (μV) to as high as thousands of volts. It may be necessary to select the correct range manually, or it may be selected automatically. Modern meters can measure both AC and DC, however, it may be necessary for the user to manually select the type of current to get accurate results. Unless designed for radio purposes, meters may be limited to only a range of AC frequencies that they can work with, and they can be affected by RF near a transmitter or the antenna.

Both analogue and digital meters were popular in the past, nowadays they are almost always digital. You are only required to learn how to use a digital meter.[334]

334 Analogue meters employed a moving coil, in which a small current would set up a magnetic field that deflected a pointer mounted on a spring, moving in front of a calibrated dial.

17.1.1 Voltage

To MEASURE VOLTAGE, the meter is connected across the points, i.e., in parallel with the circuit where voltage (potential difference) is to be determined, as shown in Figure 17-ii.

When measuring, be aware of the expected size of the voltage and any limitations of the meter. Ensure the meter is correctly set for AC or DC. When measuring AC, modern meters should display rms voltage.

An ideal voltmeter should have a high impedance, and therefore, high resistance, in order not to affect the voltage being measured by any significant current that may pass through it. Please review section 3.5 Voltage if necessary.

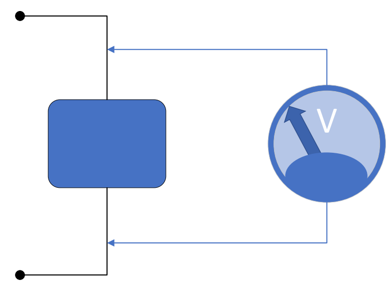

Figure 17-ii: Measuring voltage. [EI9ILB]

17.1.2 Current

To MEASURE CURRENT the meter is connected in series with the circuit where the current is to be determined, as shown in Figure 17-iii. This requires the circuit to remain open or broken, so that the current to be measured must pass through the meter.

Be aware of the expected size of the current and how long you can use the meter to measure it. Some meters only allow measurement of higher currents for a very brief moment.

An ideal ammeter should have a low impedance, and therefore, low resistance, in order not to affect the current being measured. If the meter has any significant resistance, it will affect the operation of the circuit. Please review section 3.3 Current if necessary.

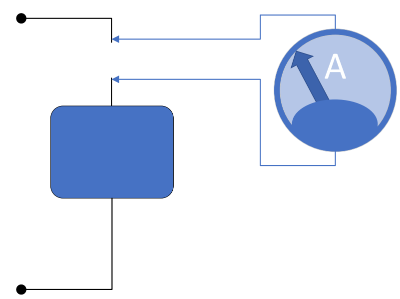

Figure 17-iii: Measuring current. [EI9ILB]

17.1.3 Resistance

To MEASURE RESISTANCE the meter is connected in parallel with the circuit or component where resistance is to be determined, as shown in Figure 17-iv.

As voltage is being applied by the ohmmeter, measurements should not be made in live circuits. If there are multiple components, their combination may determine the result when in-circuit measurements are made. If possible, measure the resistance of the components each on their own. Be careful not to exceed voltage limits of those components as the internal batteries of an ohmmeter may have sufficient voltage to damage solid state devices. Please also review section 3.8 Resistance if necessary.

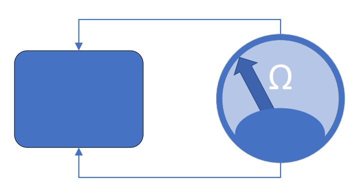

Figure 17-iv: Measuring resistance. [EI9ILB]

17.2 SWR and Power

To review the concept of DC power see section 3.10 Electric Power and Energy, and for AC power see 5.1.5 rms, Effective Voltage, Peak-to-Peak Voltage, Power. Transmitter power, including the important difference between average and peak envelope power (PEP) was covered in section 12.1 Output Power.

Power can be calculated from two measurements: voltage and current. It common to use a dedicated power meter to display AC RF power being fed into the transmission line and the antenna. Instead of using dedicated power meters, RF power can be also read from an oscilloscope when it is showing the RF envelope of the signal.

Power meters often come with an SWR meter, allowing one device to measure power and the VSWR, see section 14.9.4 Standing Wave Ratio (VSWR). By sampling the forward and the reflected power (or voltage) on a transmission line the meter shows both the transmitter power and the VSWR. The VSWR meter is often just called an SWR METER, or an SWR BRIDGE, or a REFLECTOMETER.

It is also possible to measure power using SWR meters. The net power being transferred to the antenna is the difference between the forward and the reflected power shown by the SWR meter. For example, if the forward power is 120 W, and the reflected power is 20 W, the net power going to the antenna is 100 W.

Modern transceivers will display the power they generate and the VSWR presented by the connected equipment. However, it is useful to use a dedicated, separate VSWR and RF power meter, especially when using an external power amplifier.

It is shown as part of an HF station in Figure 17-v which was discussed in section 12.13 HF Station.

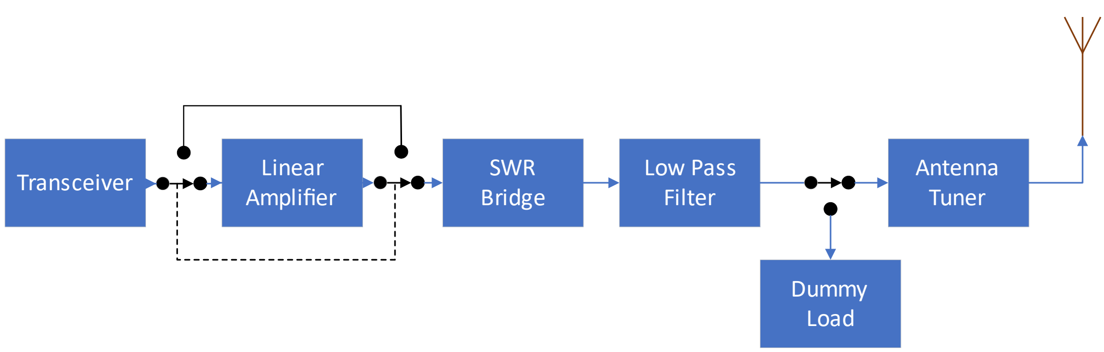

Figure 17-v: Measuring power and SWR using an SWR bridge in a HF station. [EI9ILB]

A popular design of an SWR meter, shown in Figure 17-vi, is known as a CROSS-NEEDLE SWR METER. It has two needles, one indicating the forward power, the other the reflected power. The intersection of the crossing needles gives the SWR, which is read from the centre dials, labelled from ∞ (infinity) to 1.1 in this photo.

Two realistic readings are shown in Figure 17-vii. The very best possible SWR of 1.0, or 1:1.0, would be indicated by the two needles crossing over the almost horizontal, unlabelled red line, just beneath the one labelled 1.1.

Figure 17-vi: SWR meter (reflectometer), cross-needle type. Left needle shows transmitted power, right needle reflected power. The intersection of the two indicates the SWR. [EI6LA]

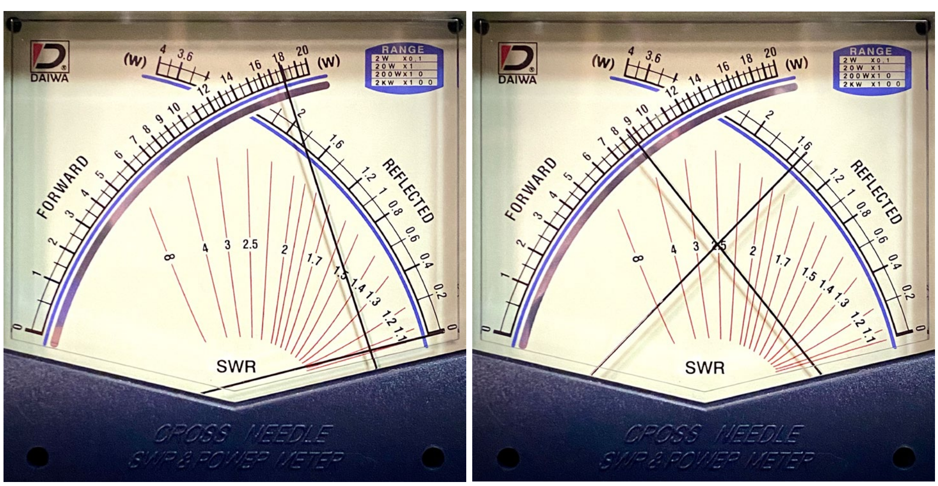

Figure 17-vii: Left: Perfect SWR of 1:1.0 and net 18 W of power. Right: poor SWR of 1:2.5 with forward power 8.6 W, reflected power 1.5 W, net power 7.1 W. [EI6LA]

This is shown on the left, above. It occurs if there is no reflected power and that needle does not move from its rest position. Only the forward power needle moves, and the value it shows, the forward power, happens to be also the net power when SWR is 1.0. On the other hand, when there are standing waves, there will be reflected

power, as shown on the right of the above figure. The intersection of the two needles over one of the red dials shows the SWR, which is 2.5, or, 1:2.5 in this case. The net power is the difference between the forward and the reflected powers.

A reading of an infinite SWR (∞) would indicate a more serious problem and the transmitter should be immediately turned off, and the issue investigated to prevent damage, especially to sensitive solid-state equipment.

Because this meter contains diodes, it should be placed before any final low-pass filters to supress harmonics.

17.3 Oscilloscope

An OSCILLOSCOPE is a general-purpose instrument for displaying electrical waveforms in the time domain, i.e., with the passage of time shown on their horizontal axis. The vertical axis shows the amplitude of the signal, usually measured as its voltage.[335] An oscilloscope has many uses in radio because it can visualise the shape of the AC waveforms it is measuring. It can help diagnose problematic signals by showing their RF envelope, discussed in the next subsection.

Oscilloscope can be a small, simple, handheld tool, or a more complex desktop device. Figure 17-viii shows a modern, desktop oscilloscope that can be used both on its own or operated from a connected computer.

The yellow trace on the screen of the oscilloscope shows a signal being analysed. The horizontal axis shows time, with each division every 500 µs (0.5 ms). The vertical axis shows voltage, with each division at 5 mV. It is necessary to adjust the size of the divisions to match the characteristics of the different signals being measured.

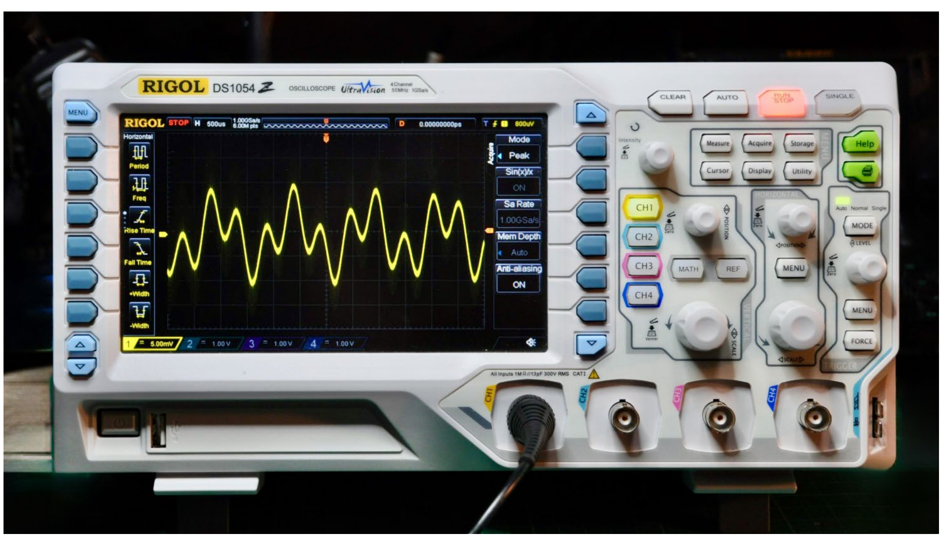

Figure 17-viii: Desktop oscilloscope. Yellow trace shows signal consisting of two combined sinusoids, used to perform a two-tone test on a transmitter. [EI9ILB]

335 See 6.2.1 Time and Frequency Domains, and the signal plots in Chapter 11 Modulation and Modes.

17.4 RF Envelope

The RF ENVELOPE of a signal is the outline, i.e., the envelope, of a *time domain* plot of a signal. It may be viewed on an oscilloscope. Some modern transceivers include an oscilloscope view of the generated signal, however, a dedicated oscilloscope will allow more control over the detail being analysed.

Many signal-related problems can be diagnosed by viewing their RF envelopes. For example, an overmodulated or an over-processed (over-compressed) SSB signal will show a pattern like that in Figure 17-ix. Compare that plot to another example of overmodulation shown in Figure 11-vii and a plot showing a normal, fully modulated signal in Figure 11-vi on page 150. Unlike the better signals, the envelope of the one shown below never seems to reach zero amplitude – it is never at rest, with some power always being transmitted. While a trained eye may immediately notice the signal's problem in this plot, there are other equipment tests that would make the issue more easily apparent.

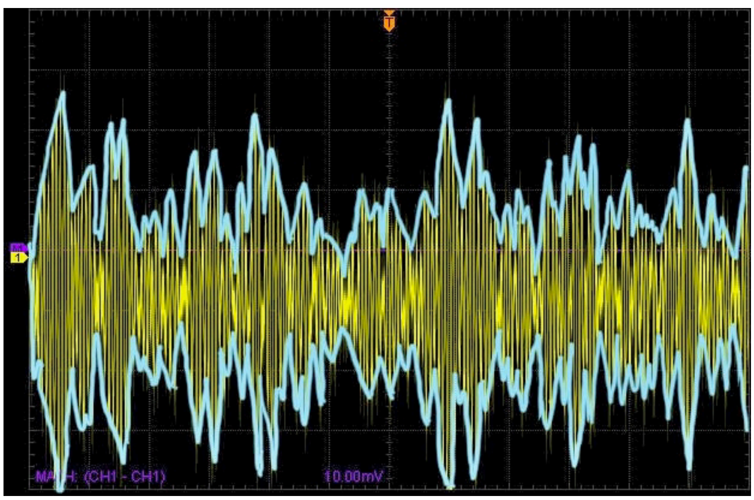

Figure 17-ix: RF envelope, cyan, of an RF signal shown in yellow, showing an overmodulated or over-processed SSB signal. [EI9ILB]

Other types of tests can be performed using an oscilloscope and a signal generator connected to the device under test. One of them is the TWO-TONE test, which is useful for diagnosing amplitude linearity and overmodulation issues of an SSB transmitter. Instead of a continuously varying pattern produced by a voice transmission, like the one shown above, which can be hard to assess visually on an oscilloscope, a two-tone test generator will produce a steady pattern that can be easily examined.[336] It will readily show non-linearities, such as flat topping caused by an overdriven

336 It is named after two audible tones that are simultaneously fed to the microphone input of the transmitter, for example 500 Hz and 1700 Hz. See en.wikipedia.org/wiki/Two-tone_testing. A related *trapezoid test* is also useful for diagnosing amplifier non-linearity.

amplifier, overmodulation, and other distortions. It can help you correctly adjust settings such as ALC and audio compression.

Example RF envelopes resulting from two-tone tests of two different transmitters are shown in Figure 17-x. The result on the left shows a well-behaved transmitter. The result on the right, however, is anomalous and requires further investigation. The overlap between the successive waveforms suggests either an overdriven stage in the transmitter, or, perhaps, poor carrier suppression in a balanced modulator, or in another processing stage.

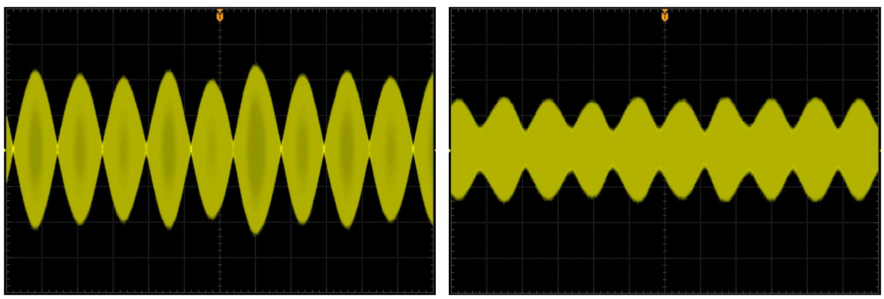

Figure 17-x: RF envelope of two-tone test of two different transmitters shown on an oscilloscope. Left: no issues found. Right: anomalous results, require further investigation. [EI9ILB]

You do not need study the two-tone test for the exam, but you do need to know its purposes.

17.5 Spectrum Analyser

A SPECTRUM ANALYSER shows the signal in its frequency domain, i.e., the horizontal axis shows the frequencies contained in the signal. It is similar in its main function to a waterfall display found in modern receivers, such as the plot showing problematic signals in Figure 18-iv on page 289. However, a spectrum analyser can be connected anywhere within the signal generation path without having to transmit or receive any radio signals. It also allows more precision and control over the measurements than the analyser built into a transceiver.

Seeing the frequency domain, i.e., the SPECTRUM of the signal, is very useful when diagnosing problematic signals. It visualises key clicks, splatter, any spurious frequencies, IMD parasitic oscillations, non-linearity, and other signal distortions, without having to rely on another person reporting those issues on their receiver's waterfall display. See also 18.2 Transmitter Distortion and Spurious Emissions.

Recall that an oscilloscope showed the signal in the time domain. Together, those two instruments can be used to visualise all aspects of the signal.

17.6 Signal Generator

A SIGNAL GENERATOR is a VFO that can generate test signals in the AF and RF ranges. Those test signals can be fed into a test circuit, or another device under test,

such as a transmitter or an amplifier, to measure their gain, linearity, or to look for distortions, spurious frequencies, and other frequency-related anomalies. An oscilloscope, a spectrum analyser, or even a voltmeter can be used to measure the signals processed and output by the device under test. Many issues can be identified by comparing the generated signals that were fed to the device under test with the output.

There are convenient devices that combine all the functions of an oscilloscope, a spectrum analyser, and a signal generator, in one unit.

17.7 Frequency Counter

It is a legal requirement that transmitter equipment must be operated on the correct frequencies within the allocated amateur radio bands and channels. The transmit frequency must be clearly shown and its measurement must be calibrated to ensure accuracy. Modern transceivers come with a built-in, accurate FREQUENCY DISPLAY that complies with the regulations imposed by the Radio Equipment Directive (RED), see section 22.12 CE Type Approval.

If building your own equipment, or using an older device, it is necessary to use a dedicated FREQUENCY COUNTER to know what frequency is being produced by the transmitter to ensure compliance with the Irish law.

17.8 Field Strength Meter

A FIELD STRENGTH METER is a device useful for checking relative field strength from a directional antenna and identifying RF hotspots.

Unless the field strength meter has been professionally calibrated, and is being remotely operated, it cannot be used to evaluate compliance with EMF safety exposure guidelines. It might, however, provide an informal, relative evaluation of the EMF fields with areas known to be compliant.

Simpler field strength meters measure only the electric field strength and calculate what the magnetic equivalent would be once in the far field of the antenna. More advanced meters can measure each field independently, which makes them more useful in the near fields of the antenna. See also 15.2 Near and Far Antenna Fields.[337]

337 EMF exposure guidelines require unperturbed measurements, i.e., measurements of fields in the absence of a human body. Any hand-held field strength meters will have their measurements significantly affected by the presence of a person. The error can be as high as 90%, making those measurements useless for the purposes of compliance evaluation. Further, any measurements in the near field of an antenna requires a separate evaluation of the electric and magnetic fields which are very different in the region nearest to HF and lower band antennas. Remote operation using calibrated equipment that follows a strict measurement protocol is difficult, expensive, and requires trained personnel.

17.9 Antenna Analyser

An ANTENNA ANALYSER is a device which comprises a wide-range oscillator that generates RF test signals, with a reflectometer (SWR meter).

An antenna analyser is also able to measure the impedance, resistance, and reactance of the antenna or the transmission line. An example of a handheld antenna analyser is shown in Figure 17-xi.

A popular type of an antenna analyser is a VECTOR NETWORK ANALYSER, VNA. It can be used standalone or connected to a computer. It is particularly useful when setting up antennas and transmission lines to predict their performance on the different bands, to estimate the SWR on different frequencies, calculate the losses on the transmission line, and in general, to adjust the antenna for best overall performance.

The example in Figure 17-xii shows an antenna being analysed for its SWR on the 80 m band. It shows that the antenna has a reasonably low, but not perfect, SWR of 1.3 at about 3640 kHz, but the SWR is as high as 3.3 on the lower end of the band, suggesting a need for an ATU, see section 14.10.

Figure 17-xi: Antenna analyser. [EI6LA]

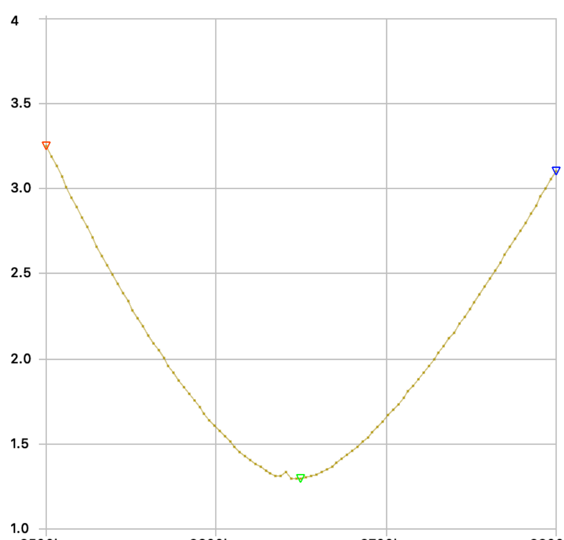

Figure 17-xii: VSWR measured using a vector network analyser (VNA), which is an antenna analyser. VSWR on the vertical axis, frequency on the horizontal, in kHz. [EI6LA]

17.10 Dummy Load

Many measurements require that the transmitter or the amplifier are engaged to transmit. To avoid unwanted emissions, the output of a transmitter can be connected to a DUMMY LOAD. Dummy loads are rated for a given level of power by stating the longest period of time that it can be fed to them. Two examples are shown in Figure 17-xiii. The larger one on the left can take considerably more power for longer than the pocket-sized one shown on the right. Exceeding the rating can cause the dummy load to leak or even burn. Be careful when making repetitive tests, as the dummy load may get very hot and not cool down enough for a subsequent test.

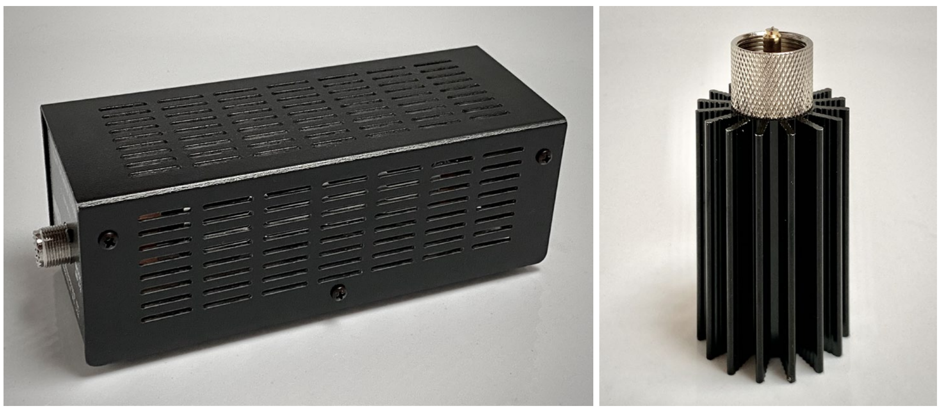

Figure 17-xiii: Dummy loads. Left: maximum 1.5 kW for 10 seconds, or 100 W for 2–5 minutes. Right: max 100 W for 5–10 seconds. [EI6LA]

A dummy load has a known impedance, usually 50 Ω. It should be constructed so that the impedance is purely resistive, with no or only a minimal reactance.

The fixed, known, purely resistive impedance of a dummy load makes it very useful for troubleshooting issues in the station. For example, if a high SWR is indicated by the transmitter, it is necessary to discover its source. This can be done by temporarily disconnecting the transmission line, any other components, and the antenna. The dummy load should be connected directly to the transmitter, at first, to ensure it has no issues. Then, as each component is being progressively reconnected to the transmitter, the dummy load should be placed at the reconnected component's other end. If SWR returns to normal when a component has been replaced with the dummy load, but remains high when the component is connected, it suggests that that component may be the source of the problematic behaviour.

Because it is used often, it is convenient to place a dummy load in a permanent position in the station, and to connect it using a switch. Figure 17-v on page 274 shows a dummy load as part of a HF station schematic.

18 Electromagnetic Compatibility, Immunity, and Transmitter Interference

FOUR EXAM QUESTIONS · SECTION A2

This chapter discusses the most important interference-related issues that can affect both an amateur radio station and those in its vicinity. Some of those issues can be avoided by using equipment that is known to comply with EMC standards. When buying equipment, look for the CE mark. See section 22.12 CE Type Approval for further information, including your right to use equipment without the mark. Other issues will require some prevention, or a few simple remedial steps.

18.1 Electromagnetic Compatibility

The ELECTROMAGNETIC COMPATIBILITY (EMC) is the avoidance of interference between any two pieces of electronic equipment. Amateur radio stations may be both the sources and the recipients of EMC interference. The INTERFERENCE is the unwanted, and potentially HARMFUL effect of receiving unwanted radio emissions, causing poor performance or a malfunction of some equipment.

For example, an outdoor security light might turn on and off unexpectedly because of interference from a nearby transmitter while it is operating. An alarm system may activate for no reason other than interference. An entertainment system's speakers might make noises or crackle during nearby radio transmissions. A poorly designed LED lighting system or a solar panel inverter or an optimiser may cause excessive noise on amateur bands making their reception difficult or even impossible. Those are all examples of interference suggesting problems with electromagnetic compatibility.

There are two routes through which EMC problems can arrive: radiated emissions and conducted emissions. Both can affect the station and any equipment within its vicinity, sometimes even further from it.

18.1.1 Radiated Emissions

RADIATED EMISSIONS are radio waves travelling through the air, which are sent and received by antennas or by any electronic circuitry that may act as an unexpected antenna.

For example, cabling used to connect devices, headphone cables, or even conductive traces on electronic printed circuit boards can act as antennas, both transmitting, and receiving unwanted radio waves.

18.1.2 Conducted Emissions

CONDUCTED EMISSIONS are RF currents directly conducted onto or from any connected wiring, such as mains cables and power lines. Although this type of interference does not travel as radio waves, its effect can be the same as if the RF was received or transmitted by an antenna.

18.1.3 Interference and Immunity

The interference emitted from an amateur transmitter falls into two main categories.

- The interference from the legitimate amateur signal to some susceptible piece of equipment, which does not have an appropriate level of immunity.
- The interference due to unwanted, excessive spurious emissions from the amateur station.

Almost all equipment sold in the EU carries the CE type approval mark. Electronics must comply with the EU EMC directives. They require equipment to have IMMUNITY from legitimate radio transmissions. Older devices might not have the immunity. For example, newer Passive Infrared Sensors (PIR), found in house alarm systems or security lights should be immune to radio emissions from amateur stations. Older sensors, however, may be affected and may activate if close enough to the antennas.[338] When a device malfunctions because of a lack of immunity to interference from legitimate emissions it is known as a BREAKTHROUGH.

There are many ways to provide additional immunity to such devices. They are discussed in section 18.1.5 Prevention.

Interference caused by unwanted, excessive spurious emissions needs remediation on the transmitting side. Taking preventative measures aimed at only increasing the immunity of affected devices may be insufficient. It may even be impossible due to much larger distances over which excessive spurious emissions can wield their harmful effects. Section 18.2 Transmitter Distortion and Spurious Emissions discusses their nature, causes, and means of avoidance.

18.1.4 Field Strength and EMC

The likelihood of interference is directly related to the strength of the EMF emitted by the station's antenna. The strength of the EMF is related to the type of the antenna, the power supplied to it, and the distance from the antenna.

An amateur station should not use more power than is necessary to make a successful contact. If possible, avoid placing any sensitive equipment close to the

338 PIR sensors detect changes in infrared fields, which are electromagnetic fields with a higher frequency than radio waves. Older PIR devices do not distinguish well enough between the frequencies, confusing even slightly stronger HF with infrared. They are not immune enough to HF.

antenna. Avoid the reactive near field of the antenna when the fields are strongest. See section 15.2 Near and Far Antenna Fields.

Other antennas, cabling, household wiring, pipes, metal fences, and other metallic objects located in the near field of the antenna will absorb and retransmit radio waves. By reacting this way, those objects may cause EMC issues by acting like additional, unexpected transmitting antennas.

18.1.5 Prevention

Many EMC issues can be reduced by reducing the transmit power. If reducing the power solves the problem, further steps should be taken to identify the cause before resuming higher power transmissions.

Antenna choice and the distance from its near fields has the most profound effect on EMC. All antennas that are too close are likely to cause some issues. However, some designs may be less prone, especially the more symmetrical ones, such as a half-wave dipole, than the less symmetrical designs, such as end-fed half-wave (EFHW) antenna, which are often located very close to the radio room. Magnetic loop antennas may seem small, but have surprisingly large near fields, considering their small size. The proximity that they invite can easily cause EMC issues with nearby equipment. High-gain antennas, such as a Yagi, should not be pointed at locations with electronic equipment.

Some antenna types, such as EFHW, rely on the presence of a good RF earth, which improves their performance, but the absence of which can also exacerbate EMC issues.

Many EMC problems are related to excessive common mode currents, usually picked up outside, often from the transmitting antenna, and travelling along the transmission line right into the radio room. Those currents will re-radiate all along the length of the line and affect nearby devices. Not only are they a nuisance that causes EMC issues, but they can also prevent equipment from working properly, often affecting some of the bands more than others. If strong, common mode currents can also cause unpleasant RF burns, see 19.3.2, inside the radio room. Common mode currents affect all cables, including parallel lines, coaxial lines, and even signalling and power cables.

Parallel transmission lines should not be bent excessively, or run near the ground or metal objects, as it may cause the currents that they carry to no longer be equal-and-opposite, and in turn, to cause feedline radiation. Consider using a coaxial line if the routing is not appropriate for a parallel line. However, common mode currents will also run on the outside of the shields of various cables, including coaxial transmission lines.

Use good quality coaxial transmission lines and good connectors. Be careful not to let water or moisture enter the coax.[339] Do not bend it more than it is designed

339 The braided outer conductor wicks moisture once it gets inside. Water will change the impedance, causing standing waves and possibly unwanted radiation near any connectors. It can also short it permanently. If burying coax underground, ensure its jacket is designed to withstand water.

for, as you may cause an intermittent short if the dielectric breaks. Always connect coaxial lines to the antenna using a balun designed for that antenna type to ensure that any common mode currents do not transfer between the line and the antenna, even if not needing to transform impedances.

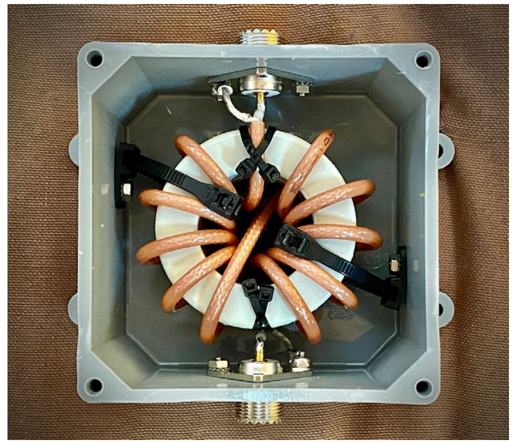

Figure 18-i: Choke. Design based on a feedline wound over a ferrite. [EI6LA]

Use chokes, such as a 1:1 current balun designed for the required frequencies and power levels to reduce common mode currents before they have a chance to enter your radio room. Chokes can be used both with coax and parallel lines.

Two popular designs are shown in Figure 18-i, and Figure 18-ii. See section 14.11 Baluns and Chokes for more examples, including an ugly balun, and further guidance.

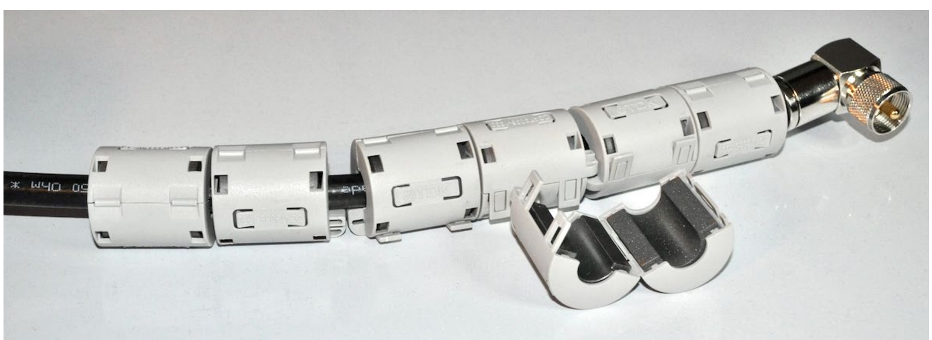

Figure 18-ii: Choke. Design based on ferrite rings threaded over a coaxial feedline, also known as a Maxwell design. [EI9ILB]

Chokes can be also placed on any other cables connected to the affected equipment, because chokes increase EMC immunity of equipment that is suffering a breakthrough. For example, place suitable FERRITE RINGS on the headphone or speaker wire to stop interference causing noise to come out of nearby loudspeakers. Use chokes to prevent malfunction of keyboards, mice, USB, and other devices connected to a computer. Figure 18-iii shows different designs which can be easily made from commercially available ferrites (toroids).[340]

340 Use a grade of ferrite appropriate for the frequency band of the interfering signal. #31 core material is suitable for many HF applications. It is better to have multiple turns of the wire through the ferrite than to clamp it onto the cable, unless using multiple toroids, as shown in Figure 18-ii.

Figure 18-iii: Different designs of ferrite-based chokes, used to prevent EMC breakthrough interference on cables attached to affected equipment. [EI9ILB]

Use appropriate filters at the output of the transmitter or at the input to the electronic device being interfered with. Use a low-pass filter with a cut off at 30 MHz as part of the overall HF station design, see Figure 12-xviii on page 187. A VHF or UHF station should use an appropriate band-pass filter instead.

18.1.5.1 *Shielding and Earthing*

Many EMC problems can be prevented with good shielding and earthing. Your station's mains power supply must have a functioning, good quality electrical earth.

Equipment should be adequately SHIELDED, generally in an earthed metal enclosure, to prevent radiation leaving or entering the device. The earthing points of the equipment should be connected to a good earth. See section 19.4.2 Protective Earth, including the footnotes, for suggestions how to connect equipment to earth.

! Never operate transmitters and amplifiers with their covers or shields removed. Not only does the removal of shielding cause EMC problems, but it is also unsafe, both from an electrical and EMF safety point of view. See 19.8.6 Interior of Transmitters and Power Amplifiers.

Coaxial transmission lines benefit from a connection to a good earth at several places, notably where they enter the building, both for electrical safety, but also to help dissipate common mode currents that may be flowing on their outside.

A properly designed RF earth which has a very low RF impedance, and does not behave like an antenna, and which is capable of dissipating considerable RF currents, can help prevent many EMC issues. It can even improve the operation of some types of antennas. However, RF earth is a complex subject. Seek advice from experienced professionals before installing RF earth. Above all, any earthing installation, including RF earth, requires careful observance of the relevant safety regulations. In Ireland, an RF earth, like any other earth in a domestic environment, should be bonded to the house's *protective earth* and certified as such by a qualified electrician. See comments in section 19.4.2, especially footnote 355 for further information regarding RF earth.

! Do not compromise the safety of your electrical installation by using an RF earth that has not been installed in line with the regulations.

18.2 Transmitter Distortion and Spurious Emissions

Different types of distortion can be caused by transmitters. Unlike in a receiver, where the distortion impacts only the listening station, distortion in a transmitter leads to significant interference to other users of the radio spectrum. It can cause EXCESSIVE SPURIOUS EMISSIONS, i.e., spurious emissions in excess of the regulatory limits, even on bands and frequencies which are not allocated to amateur radio use.

! You must not cause interference by generating *excessive* spurious emissions. It would be inconsiderate to others, and you would be in breach of your licence conditions.

All transmitters and receivers contain one or more internal power amplifiers, regardless of any additional, external ones. Even the best linear amplifiers are never perfectly linear. However, they all lose their linearity when they are overdriven, and then they are likely to start generating excessive spurious emissions. See section 10.7.4 Distortion from Amplifier Non-Linearity.

These types of distortion can affect amplifiers used for reception and transmission. This section focuses on the transmitter distortion because of the harmful nature of the interference it causes. On the other hand, significant distortion in a receiver will also make successful communication hard or even impossible, no matter the mode of communication. There are two main types of distortion caused by amplifiers and the transmitters that contain them that leads to harmful interference.

- A HARMONIC DISTORTION causes otherwise insignificant replicas of the input signal to be amplified much more than the original signal itself. Those HARMONICS exist at harmonic frequencies, i.e., multiples of the input signal's frequency. Normally, they are unnoticeable. If excessively amplified due to the non-linearity of an amplifier causing harmonic distortion they can cause significant interference with both nearby frequencies, but also on different bands.

- An INTERMODULATION DISTORTION (IMD) happens when the non-linearity of an amplifier amplifies unwanted frequency mixing artefacts much more than the original signal. Different frequencies of the original signal would normally mix, forming weak, insignificant new frequencies.[341] IMD causes those unwanted products to be amplified more than the original signal, distorting audio, or causing loss of data in a digital signal.

Distortion manifests itself as distorted audio or corrupted data, and at worst as harmful interference, including splatter and key clicks.

The HARMFUL INTERFERENCE from these causes will make your signal appear on a frequency on which you were not intending to transmit. For example, harmonic distortion of a signal on the 40 m band can cause significant interference to the 20 m band, and even outside of legal band limits.

The SPLATTER in AM and SSB sounds like a heavily distorted, clipped echo of another conversation that despite being loud is not understandable, giving it a tiring, pulsating quality. In FM, it can make another transmission hard or impossible to understand. [342] It will mainly affect nearby frequencies, including neighbouring channels, because of utilising an excessively wide bandwidth, and so affecting other users of the spectrum.[343] The term splatter is also used to describe interfering replicas of the original signal on other frequencies.

Similarly, KEY CLICKS appear on nearby frequencies, and they sound like loud, hollow, distorted echoes of Morse signals. They usually begin with an improperly shaped CW keying waveforms, for example, by not using a sufficiently long rise time, see section 11.8.3. An overdriven amplifier and the use of higher power levels will exacerbate the problem by amplifying both the harmonics and causing IMD from the excessive use of the bandwidth.

Figure 18-iv on the next page shows an example of key clicks causing harmful interference to nearby frequencies. This is harmful to others who are unable to use a large range of frequencies on this band, and perhaps even on other bands. What started as a somewhat confined issue of a poor CW keying waveform grew into a source of major interference.

This problem affects not only CW and other ASK, but also any other digital modulation mode, including FSK and PSK. Figure 18-v at the bottom of the next page shows FSK splatter and key clicks, most likely caused by the lack of appropriate filtering, or an incorrectly configured modulation technique, without appropriate PULSE SHAPING, perhaps in tandem with an overdriven amplifier.

341 When two signal frequencies mix in a radio circuit, they add and subtract from each other, creating two new frequencies (3rd order IMD, also referred to as 3IMD, IMD3) plus additional frequencies, at sums and differences of the multiples of those frequencies (4th, 5th order and so on IMD). You can see those artefacts on a waterfall display as lines that appear on both sides of a signal produced by an overdriven, non-linear amplifier.

342 Splatter in FM can make voice on nearby channels sound strange, for example, give it a *Donald Duck* effect, or even cause them to become entirely unreadable.

343 The excessive bandwidth is unnecessary, a nuisance, and against guidelines. A distorted SSB transmission may occupy over 7 kHz of bandwidth instead of the 2.7 kHz guideline. A distorted CW signal may interfere well over 2 kHz of bandwidth, instead of the usual 50–200 Hz.

Distortions may have other causes. An overactive ALC circuit fed with a mixture of normal and overdriven signals may cause sudden clipping of the input signal levels as it tries to reduce the cause of overdriving. Such sudden adjustments may cause signal clipping and non-linearity, and further harmonic distortion and interference.

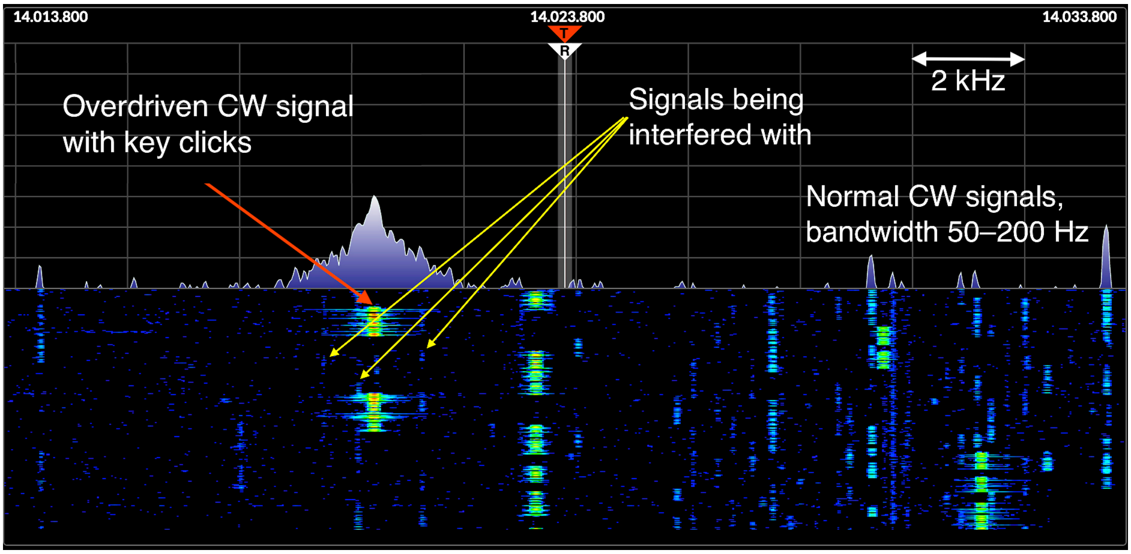

Figure 18-iv: Key clicks and an overdriven CW signal causing excessive bandwidth use of over 2 kHz instead of 50–200 Hz. Bottom half: waterfall spectrogram (frequency on the horizontal, time on the vertical axis). Upper half: signal amplitude in the frequency domain, on the 20 m band. [EI6LA]

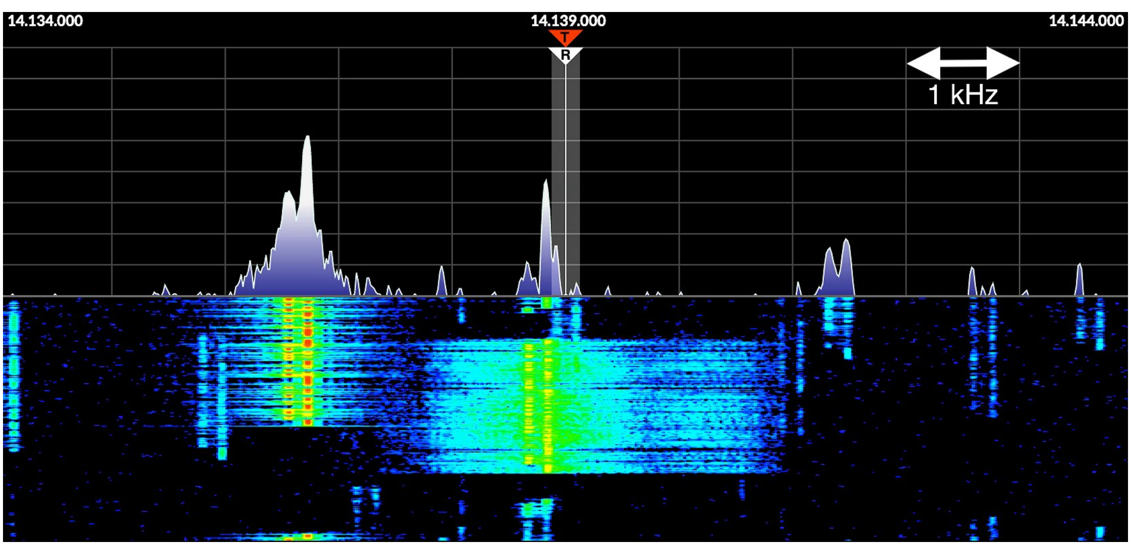

Figure 18-v: Interference caused by unfiltered, improperly shaped FSK signals. The central one occupies more than 3 kHz of bandwidth. The one on the left occupies over 2 kHz and has key clicks extending 3 kHz. Notice the normal signal in the centre, just behind and above the interfering one. It has the correct bandwidth of 300 Hz, just like the signals on the very right of the plot. [EI6LA]

As a rule of thumb, the OVERDRIVEN AMPLIFICATION is the primary cause of most types of distortion that you are likely to encounter. It can be caused even without using external amplifiers by feeding an excessively high (overdriven) level of audio, digital or analogue, to the transmitter. See also section 12.5 Problems Affecting Transmitters.

18.2.1 Spurious Emissions

No device is perfect. Even the highest quality ones will generate some unwanted emissions, even when not overdriven, and whilst used within the limits of their specifications. The unwanted emissions are known as SPURIOUS EMISSIONS, or as SPURIOUS RADIATION. They happen, because:

- All transmitters and amplifiers have some non-linearity.
- All filters leave a residue of unwanted frequencies that they are unable to fully remove, and which can cause unwanted emissions outside of the selected bandwidth.
- Frequency mixers, modulators, multipliers, and converters create a small level of unwanted intermodulation products.
- An amplifier can oscillate slightly near its working frequency, a problem known as the SELF-OSCILLATION.
- Spurious, PARASITIC OSCILLATIONS can be caused by an internal feedback loop that causes an amplifier to oscillate at a frequency not necessarily related to the working frequency.
- Frequency synthesisers generate small levels of unwanted signals and phase noise.
- Even small amount of AM and SSB overmodulation can generate unwanted frequencies. See section 11.4.1.2 AM Modulation Index for an example.[344]

High quality filters greatly reduce spurious emissions, but it is impossible to prevent them completely. Regulations allow a small level of spurious emissions. The strict regulatory limits are outlined in ComReg Amateur Station Licence Guidelines 09/45. See also section 22.11 Technical Requirements. Any spurious emissions in excess of the regulatory limits, are EXCESSIVE SPURIOUS EMISSIONS. They are illegal and must be remedied at source.

344 Unwanted frequencies can be also generated by FM over-deviation, when the highest frequencies in the input signal (modulating signal) exceed the chosen value of peak deviation.

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19 Safety

FIVE EXAM QUESTIONS · SECTION A1

! This section of the guide has been provided to help study the *exam syllabus*. It is not intended as a safety manual nor as a substitute for one. NO RESPONSIBILITY OR LIABILITY will be accepted by the authors or by the IRTS for any event, accident, or consequence of using this guide. It is your responsibility to comply with all safety regulations, and to apply common sense.

Amateur radio has shown itself to be generally safe for over a hundred years of its existence. There are, however, a few risks that you need to be aware of and which you need to mitigate not only for your own safety, but also for anyone near your station.

19.1 Radio Safety and The Irish Law

The Wireless Telegraphy (Amateur Station Licence) Regulations 2009 make you legally responsible for the safety of your station and its operation. The regulations focus both on the overall aspects of safety and specifically in relation to non-ionising radiation emissions. There are three relevant sections of the regulations that deal with matters of safety as a condition of your licence. You are legally required to:

1 Ensure that the installation of the apparatus, i.e., the station equipment, or any of its parts, is effective, and its maintenance and operation is carried on, in such a manner as to ensure that the safety of persons or property is not endangered.[345]
2 Ensure that non-ionising radiation emissions from the station equipment are within the limits specified by the guidelines published by the International Commission for Non-Ionizing Radiation Protection (ICNIRP), any radiation emission standards adopted and published by ICNIRP, or its successors, and any radiation emission standards of the European Committee for Electrotechnical Standards, and any radiation emission standards specified by national and European Community law. This requirement applies to each part of the station as well as to the *aggregate* emissions in case of multiple transmitters or antennas.[346] While several regulatory bodies are mentioned in the legislation, the ComReg Amateur Station Licence Guidelines 09/45 specifically require you to ensure that non-ionising radiation emissions are within the limits specified by the guidelines published by the ICNIRP.
3 Observe good site engineering practice in accordance with ComReg guidelines, which specifically require you to follow mechanical and electrical construction best practice.[347]

345 Wireless Telegraphy (Amateur Station Licence) Regulations 2009 section 7.(1)(k).
346 Wireless Telegraphy (Amateur Station Licence) Regulations 2009 section 7.(1)(e) and 7.(1)(f).
347 Wireless Telegraphy (Amateur Station Licence) Regulations 2009 section 7.(1)(l).

The remainder of this section suggests several ways that will help you comply with those obligations. However, it is ultimately your personal responsibility to ensure that you know and that you do everything necessary to comply.

19.2 Equipment Labelling and Access Control Requirements

ComReg regulations require that:

- the station should have all controls, meters, indicators, and terminals clearly labelled
- details of the main and any auxiliary power supply from which the equipment is intended to operate shall be clearly indicated
- important controls which change the system parameters shall be accessible to qualified personnel only
- all wireless telegraphy equipment shall be labelled with the manufacturer's trademark, type designation, and a serial number.

19.3 Electricity and The Human Body

The human body is a good conductor of electricity. Typical resistance from hand to foot is low and a considerable current can flow through the body from a high voltage source to earth.

! Small currents of just **50 mA** can disturb the electrical conduction system of the heart causing it to go into ventricular fibrillation, a fatal rhythm disturbance.

It is the current that kills. The mnemonic *it's the volts that jolt but the mills (milliamps) that kill* may help you remember this. Even voltages as low as 30 V can kill in adverse circumstances, given a sufficient current. A conduction path from a voltage source through one hand, across the chest cavity to the other hand grounded is the worst scenario.

! Always keep one hand behind your back when working on high voltages.

19.3.1 Dealing with Electric Shock

If you suspect someone is experiencing an electric shock:

1. **shut off the power** before touching the person
2. ensure the person is in a safe place
3. call for help
4. commence Cardiopulmonary Resuscitation (CPR) if necessary and if you are qualified to do so.

19.3.2 RF Burns from Direct and Near Contact with RF Currents

The most immediately hazardous biological effect of exposure to RF currents is an RF BURN. RF burns are associated with physical direct or near contacts with a conductor that is energised by RF currents. The best example of such an energised conductor is the antenna while it is transmitting.

The RF current that is flowing into the contact point on the skin may be sufficient to cause rapid high temperature elevations to cause a burn. RF burns can be very painful. Depending on the current and the frequency, an RF burn may be superficial, or quite deep and it can cause damage just like a burn from a very hot object. If you receive an RF burn, cool the skin down with tepid running water. Seek medical help if the burn is extensive or deep, just as you would with a traditional burn.[348]

RF burns can be caused even before you touch an energised conductor. An electrical arc can form between the skin and the conductor if the RF voltage is sufficiently high, and you are near the conductor. You can get such a burn twice: prior to a physical contact, and once again, when you touch the energised conductor.

! Never touch antenna elements or other conductors unless you are confident that they are not energized.

! Ensure that no other person or animal can touch your antenna when transmitting.

! Due to the risk of an electrical arc causing an RF burn, avoid standing close to those parts of the antenna where the voltage is high, such as the ends of a half-wave dipole, or the top of a vertical quarter-wave antenna.

The only exception are antennas designed to be touch-safe, such as the short *rubber duck* antennas used on handheld transmitters. It is still a good idea to point such handheld antennas away from the head and face when transmitting, or to keep them altogether away from body. Consider also using a separate speaker-microphone with handhelds.

Conductors other than antennas can also be unexpectedly energised with RF currents. For example, improperly earthed equipment, including transceivers and amplifiers, can carry RF currents on their metal cases. Those currents can come from different, unexpected sources. Poorly designed antennas, or parts of an antenna transmission line, such as the outside of a coaxial cable's shield, which is just under its plastic jacket, may be picking up sufficient currents during transmissions to deliver them to any connected yet improperly earthed equipment in your radio room.[349] Those currents can then travel to other connected equipment, including microphones and Morse keys. While RF burns caused by such currents are unlikely to be as dangerous as those caused by touching the antenna, they will be painful.

348 Ice used to be recommended to treat burns, but the current advice suggests *tepid* or cool water, not ice or iced water. See www.nhs.uk/conditions/burns-and-scalds/treatment and www1.vhi.ie/blog/articles/caring-for-burns-the-dos-and-donts-of-home-treatment.

349 RF current flowing on the outside of a coaxial cable is usually a common mode current. It is a nuisance. See section 14.11.2, 1:1 Current Balun and Common Mode Choke.

19.4 Mains Power Supply

All electrical installations in your station must comply with the current Irish electrical regulations. The mains supply to your station, including its safety devices, and any protective earth (ground) that you already have or that you have added to your station should be installed or certified by a qualified electrician.[350] You should receive a *Safe Electric National Rules for Electrical Installations Completion Certificate* confirming the standard of the works, including the correct functioning of the protective earth.

If your electrical installation is old and has not been looked at for some time, consider having it inspected by a qualified electrician, especially if you plan a more extensive installation that includes any changes to the earth and ground system.

The importance of electrical safety cannot be overstated. An electrical installation compliant with Irish regulations, with a working protective earth, residual current devices (RCDs), fuses, and appropriate switches is an essential part of every amateur radio station.

19.4.1 Supply Safety: Switches and RCDs

Ordinary 230 V circuits are the most common cause of FATAL ELECTRICAL ACCIDENTS. Power to the amateur station should be controlled by a double pole on-off MAIN (MASTER) SWITCH which breaks both the live and neutral. Its location and purpose should be known to all family or club members.

RESIDUAL CURRENT DEVICE (RCD) or EARTH LEAKAGE CIRCUIT BREAKER (ELCB) should be fitted in the mains feed to the station in accordance with electrical regulations. An RCD or ELCB cuts the power in a fraction of a second if the current flowing in the live and neutral become unequal by the rated amount stated on the RCD, usually 30 mA. This can provide safety if that amount of current would flow from live, perhaps through a person's body, to earth, instead of to neutral, in case of a fault. These RCDs are generally located in your electrical distribution board and should be tested frequently, at least twice per year, by pressing the test button.

! A lethal current of 50 mA could flow through you to earth without blowing a traditional fuse or tripping an Miniature Circuit Breaker (MCB). However, an RCD would trip if it detected at least 30 mA of current somehow no longer flowing to neutral.

350 By law, if an individual or a company intends to carry out electrical work in a domestic setting in Ireland, they must register with *Safe Electric*. See safeelectric.ie/find-an-electrician to find a qualified electrician. For more information about this regulation see Commission for Regulation of Utilities and the Department of Enterprise, Trade and Employment. See www.cru.ie/home/home-safety/electrical-works-in-your-home.

19.4.2 Protective Earth

All exposed metal surfaces should be PROPERLY EARTHED through a low resistance path to earth, provided by the earthing system.[351] The EARTHING SYSTEM used in Ireland is known as TN-C-S.

All station equipment should be properly earthed (grounded). Since commonly used radio equipment relies on 12–14 V DC power, which does not provide its own earth or a ground, you need to connect your equipment's dedicated earth terminals to a suitable earthing point. You may need to install such an earthing point while you are designing your station – ask a qualified electrician for help.

Connect your equipment using earth straps or cables of a sufficient diameter or cross-sectional area to handle not only the maximum possible device current, but also currents from other nearby devices that may connect to it.[352] Avoid daisy-chaining earth connectors from one device to another. Instead, connect each device directly to a common earthing point[353] using a dedicated strap or a cable.[354]

Microphones and Morse keys should be either fully insulated or properly connected to an earthed chassis or a common earthing point.

If your antenna type requires an RF earth connection to function correctly, make sure that its earth or ground connections, including any earth that is connected to coaxial transmission lines, complies with electrical regulations.[355]

Ensure that all forms of earth or ground in your station are PROPERLY BONDED to the house's protective earth, in accordance with regulations. Ask a qualified electrician to check and certify the safety of your protective earth.

! Having multiple earths that have not been bonded together can create lethal hazards in a domestic environment.

351 Ideally, the path to earth should not only have a low resistance, but also a low *impedance* at RF, and be capable of carrying considerable RF currents. Such earth could provide both mains AC supply safety and a way to dissipate RF currents.

352 Flat, wide straps, or wide braided straps, of a sufficient width, provide a low-resistance path to earth for mains current. They are also better at conducting RF currents to earth than traditional cables. Wide straps have low inductance and, therefore, lower impedance at RF than narrow, round cables. A wide conductor will usually be thick enough to provide a low AC resistance. Braided straps are not as good as flat straps in terms of RF impedance, however, they are flexible. Braids must be protected from ingress of water that can corrode them and irreversibly ruin their good RF conductivity.

353 Also known as a *bus bar.*

354 Same-length straps or cables can be connected from each device to a common earthing point. Such a *star connection* can be very unwieldly in a large station. An alternative is a wide, thick, flat copper conductor, or a copper pipe, behind the bench. All devices are individually connected to it with short straps. The conductor behind the bench is connected to the earthing point with its own strap.

355 This is a complex subject. An earth/ground required for an antenna's RF performance has different requirements to the more important *protective earth* needed for both AC and RF electrical safety. A good RF earth is necessary for some antennas to function correctly or to achieve good performance, and it can sometimes help to reduce the noise levels. However, never install it in a way that would compromise electrical safety! In Ireland, such an RF earth should be bonded to the house's protective earth and certified as such by a qualified electrician. Find out if your antenna type needs an RF earth. It may not be practical unless the RF conductors are kept short and preferably flat and wide.

! When researching the subject of earth, grounding, and bonding, beware of advice from other countries, including the United States, which could be dangerous to follow in Ireland. The protective earth systems used in Ireland, and some parts of the UK, are significantly different from the designs advocated for radio amateurs in the USA and in other parts of the world.[356] By following incompatible advice, you are likely to create a lethal hazard in your home if a fault occurred in another house or a building that may be far away from you, but which shares your electrical supply. Always follow Irish electrical regulations and employ the help of a qualified electrician. Insist on receiving a Safe Electric certificate for any works done on your installation.

19.4.3 Wiring and Plugs

Wiring should be adequately insulated to avoid short circuits and electric shock. The wire should also be of an appropriate cross-sectional area and power rating for the maximum current involved. When wiring a mains plug for 230 V AC, such as shown in Figure 19-i, remember the colour coding of the wires.

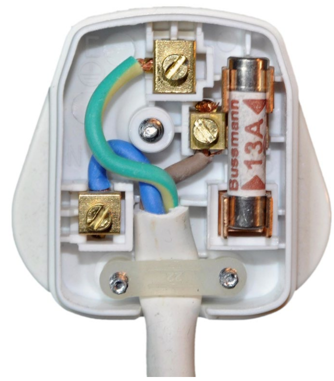

Figure 19-i: Wiring of a mains plug used in Ireland and the UK. [EI9ILB]

- The LIVE conductor is **brown**
- The NEUTRAL conductor is **blue**
- The EARTH conductor is **green with a yellow** stripe

19.4.4 Fuses

! Switch off or unplug the device before replacing fuses.

Always use a fuse with the lowest current rating suitable for the circuit to achieve the highest level of protection. The fuse is supposed to break as soon as the current is higher than that required by the device. However, do not use a fuse that matches exactly the current and the voltage of the circuit because it could trip often. It is necessary to add a small margin, depending on the type of the fuse. For example, if the maximum current the device needs is 2.5 A, use a fuse rated at 3 A, rather than a much higher rated one, such as a 13 A fuse.

356 Modern installations in Ireland use a protective earth system known as TN-C-S. In Ireland, it comes with several types of additional, stringent bonding and earthing provisions made by the electricity network operator (ESB). Unlike in other countries, every second overhead pole is provided with its own earth rod. Similar methods are used for subsurface supplies. The entire ESB network implements modern bonding and earthing principles. Those provisions are beneficial for safety and for radio purposes. Popular American advice, including some ARRL books, focuses on different TN-C-S, TN, or TT systems and their variants. The UK uses TN-C-S but does not always implement bonding and earthing in the same way as in Ireland. Following foreign advice on an Irish installation creates a significant hazard with a risk of lethal currents appearing throughout the house, including bonded metal surfaces such as sinks and water fittings, risk of fire, and a risk to life.

The fuse will blow quickly only when the overload is severe. It does not provide any protection during the time it takes to blow, which may be considerable, depending on type of the fuse.[357]

You may need to install fuses in many places: in mains plugs, as in Figure 19-i, on DC cables, in DC power distribution strips, and inside appliances. Always aim for the highest protection.

A fuse or fuses of appropriate values should be fitted on the outputs of any DC power supplies as close to the source of power as possible. It is common to have fuses on both the positive and negative DC cables. It is convenient to do that using a fused power distribution connector (strip), which usually accept automotive style, flat fuses.

A mains AC plug fuse of an appropriate value should be fitted in the live lead only, on the equipment side of the switch. This helps protect the wiring and the equipment in the event of a fault and a greater than the fuse rating current flowing in the circuit.

The maximum power that can be drawn at the following levels of current from the 230 V mains supply is shown below. Bear in mind that these values offer no margin, which would cause the fuses to trip if this level of power was drawn. Use either a slightly larger fuse rating or ensure this level of power is never drawn.

$$3\text{ A} = 690\text{ W} \qquad 5\text{ A} = 1150\text{ W} \qquad 13\text{ A} = 2990\text{ W}$$

19.4.5 Valve Equipment and High Voltage Power Supplies

! Lethal voltages and currents are present inside valve transmitters and power amplifiers and their high-voltage power supplies.

Micro switches should be installed so that high voltage supplies for valve (vacuum tube, see 10.3) power amplifier stages are automatically disconnected when the cover is removed.

In high voltage power supplies a bleeder resistor should be connected across each smoothing capacitor to allow them to discharge after the power is switched off. Unless discharged, those capacitors can hold charge for a very long time, months or even years. Bleeder resistors are a frequent point of failure in high voltage power supplies. Never rely on them.

! Always use a shorting stick to ensure that high voltage smoothing capacitors are discharged before working on a power supply.

Provide a low-resistance DC path to ground through a high-current RF choke at the output socket of a valve transmitter or a linear amplifier. This should prevent a failed (shorted) DC blocking capacitor in the anode circuit from putting a high DC voltage on the antenna.

357 The time a fuse takes to blow depends on how close the conducted current is to its rated current. There are different types of fuses. Some handle a brief excessive current while others blow very fast.

19.4.6 Adjusting Live Equipment

! Always switch off, unplug equipment, and check to ensure that the voltage has disappeared, before undertaking work.

! If using a voltmeter or a multimeter to check for the absence of voltage, always check first on a known safe source to prove that the instrument is working correctly.

When adjustments must be made to equipment that has to be powered on, use a plug-in RCD in the mains socket unless the circuit is already protected with a dedicated RCD. Power should disconnect if more than 30 mA flows to earth, helping you avoid a shock.

Remove watches, necklaces, rings, and other jewellery which might cause a short circuit. Use one hand only to make adjustments and ensure that the other hand is not grounded. Never provide a current path from one hand across your chest cavity to your grounded other hand.

! Always keep one hand behind your back when working on high currents or voltages.

19.5 Mobile and Battery Safety

- Mount equipment securely.
- Provide fuses on both positive and negative battery leads. Never short-circuit a high-capacity battery as there is a risk of fire or explosion.
- Obey the law and use a hands-free microphone to avoid being distracted from driving. Major adjustments, such as band changes, should be made when stationary. Obey laws and regulations, including use of communication devices when driving.
- Ensure there is an easily reachable main (master) two pole power switch.
- Switch off engine and radio equipment when refuelling.
- Carry a suitable fire extinguisher.

19.6 Antenna (Aerial) Safety

19.6.1 Mechanical Safety

Antenna mechanical installation should follow good engineering practice. Towers, masts, and rotators should be rated for the loads, including wind load. Guy ropes should be secured to the ground 60–80% of the mast height away from the base of the mast.

Be very aware and careful of overhead power lines and what may happen if the antenna breaks or falls. Towers and masts should be located twice their own height away from nearby power lines, people, and property.

19.6.2 Lightning

If the risk of lightning is a concern in your area, and your antenna uses a tall tower, consider providing ground rods for it. Such towers should have each leg connected to a separate ground rod and these should be bonded together. Ground rods should be at least 1500–2400 mm long and at least 12.5 mm in diameter. They should be made of copper, galvanised steel, or stainless steel. Several should be used spaced apart, and they should be bonded together with a large diameter, heavy conductor. Consult a qualified electrician to check if these ground rods require bonding to the house's protective earth, as that may depend on the distance from the tower and the other electrical connections and grounding systems.

Fit STATIC DISCHARGERS (lightning arrestors) in antenna feeders. In open wire feeder use spark gap type static dischargers. Although nothing will protect your equipment in case of a direct lighting strike, they can save it from transient high voltages in case of a nearby strike. If lightning is a concern in your area, always consult an expert. Bear in mind that the correct place for lightning protection is outdoors and not inside the house.

When thunderstorms are forecast disconnect and ground all feeders, preferably outside the building. All antennas should be earthed when not in use.

19.7 Chemicals

Soldering should be carried out in a well-ventilated area. Avoid inhaling the fumes and consider using lead-free solder. Wear suitable eye protection as hot solder may splatter. Caution is required with solvents and cleaners: avoid inhalation and skin contact.

Use components that comply with the Reduction of Hazardous Substances (RoHS) European directive whenever possible. Be careful when working on old circuits as their components may contain hazardous materials whose use was permitted prior to the introduction of more recent EU regulations.[358]

19.8 Non-Ionising Radiation and Electromagnetic Field Safety

You are required, by the Irish law, to comply with the ICNIRP (International Commission on Non-Ionizing Radio Protection) guidelines. These guidelines are available in two publications.

- 1998 ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz)[359]

358 The understanding of safety has changed over the years. Many substances have been eliminated, like lead, mercury, cadmium, polybrominated biphenyls, hexavalent chromium. Even uranium was once used in the manufacture of glass for the early transmitting vacuum tubes.

359 www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf

- 2020 ICNIRP Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)[360]

The law does not state which of those two guidelines you are required to follow, and both editions are in current use. There are significant differences between the 1998 and 2020 guidelines. The 2020 guidelines have been expanded to cater for new types of mobile phone transmissions. Unfortunately, both of those guidelines, and especially the 2020 edition, are highly technical, complex, and difficult to interpret for amateur station use. However, the remainder of this chapter provides practical compliance suggestions.

19.8.1 Emissions and the Exposure Limits

The ICNIRP guidelines specify many types of exposure limits, some of which are known as *reference levels* and other as *basic restrictions*. For simplicity, this study guide refers to all of them as EXPOSURE LIMITS.[361]

It is important to understand the difference between exposure and emissions as the two terms are sometimes mixed up.

- The EMISSIONS are produced by the antenna. They represent the signals transmitted from it. Emissions can be characterised for the purposes of safety by the EMF strengths and power densities. ICNIRP guidelines contain no restrictions on emissions as such. Instead, ICNIRP guidelines focus on exposure to humans.
- The EXPOSURE is the emissions that reach a person and are absorbed by their body.

Complying with the exposure limits therefore requires that people are not present in locations where they could be exposed to emissions above the ICNIRP limits while the transmitter is operating. If people cannot access such locations, then exposure cannot occur and compliance is achieved irrespective of the transmit power, the antenna configuration, or any emissions associated with the station.

Just because there may be areas in an amateur station in which the field levels stated in the ICNIRP exposure limits could be exceeded does not necessarily mean that exposure guidelines would be exceeded.[362] A person must be present in those areas for a period of time to become potentially, but not necessarily, exposed to the emissions. That period might be shorter if the emissions are higher, or longer, if they

360 www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf

361 There are technical differences between basic restrictions and reference levels. According to the ICNIRP methodology, *reference levels* have been derived from a combination of computational and measurement studies to provide a means of demonstrating compliance using quantities that are more easily assessed than *basic restrictions,* but that provide an equivalent level of protection to the basic restrictions for worst-case exposure scenarios. In most cases, the reference levels will be more conservative than the corresponding basic restrictions.

362 The reason why exposure guidelines would not be necessarily exceeded is because the exposure limits are stated in terms of time-averaged values of field strength, or power density, and spatially averaged values of the field strength. The time spent in an area of concern, and even the shape and height of the body can yield different averaged values of exposure.

are low. Therefore, the location and the type of the antenna must be considered in relation to where people may be while you are transmitting.

The ICNIRP guideline exposure limits are stated in terms of time-averaged and peak value electric and magnetic field strengths. Induced current densities, whole-body and localised Specific Absorption Rates (SAR), and power densities are also specified in the guidelines. Different limits apply to different frequencies. Most of the limits are specified on a time-averaged basis, i.e., over a period, such as 6 or 30 minutes, during which the field strengths are averaged.[363] Additionally, some of the limits in the newer, 2020 guidelines, are specified as instantaneous peak values that should not be exceeded even momentarily.

The ICNIRP exposure limits have been calculated in such a way that there is always a large margin of safety in case of an accidental, one-time overexposure.[364]

Two sets of limits exist: a lower, more stringent one for the members of the general public, which includes all pregnant women, and a higher one, allowing greater field strengths, for occupational exposure for people knowingly working in places where they can be exposed to significantly strong RF EMF, such as in the radio industry. Irish regulations do not state if radio amateurs should consider themselves to be general public or occupationally exposed.

If you organise an event, such as a field day, or a stand at a public gathering, you have the duty of care towards the general public. Make sure you are prepared to knowledgeably answer questions about non-ionising radiation exposure to anyone who may ask. Ensure there is no chance of unintended exposure by considering the location of the antennas at such events. Make sure that any handheld device that you let a member of the general public use is compliant with safety regulations and guidelines.

There are other guidelines for limits of exposure to non-ionising radiation.[365] Those guidelines can differ significantly from those of ICNIRP; however, you are legally required to follow the ICNIRP guidelines in Ireland.[366]

19.8.2 How to Comply?

Arguably, the only way to ensure compliance is by performing actual measurements of the field strengths and of all the other criteria listed in the ICNIRP guidelines. Those measurements are difficult to perform, require experience on the part of the

363 Some ICNIRP limits use averages of squared field strengths.

364 The way ICNIRP achieves a safety margin is by applying large *reduction factors* to the calculated exposure limits. After establishing the level of exposure that could cause an adverse health effect, that level is reduced by a factor of at least 2 and as much as 50 to arrive at the guideline limit. This makes it extremely unlikely that radiofrequency-induced exposure at the guideline limit would cause hazardous effects on the human body.

365 Several organisations publish non-ionising radiation exposure guidelines, including: ITU, WHO (World Health Organisation), IEEE (Institute of Electrical and Electronics Engineers), and FCC (Federal Communications Commission in the USA).

366 Some of the guidelines not only differ but even appear to contradict each other. For example, the consequence of 2020 ICNIRP guidelines related to 1–10 MHz EMF radiation seems to contradict some of the guidance provided by the FCC for those frequency ranges.

person performing the measurements and always require the use of specialized, calibrated, and expensive equipment to be relevant.[367]

Because of the unique situation of amateur stations, they are usually located within the antenna's near fields, especially in the reactive near field, see section 15.2. Strong EMF exist in those regions near the antenna because they contain the electromagnetic energy that has not yet propagated away, and which is still interacting with the antenna and nearby objects. Conditions in this region are important, and very difficult to either measure or calculate. In the near field region, a separate measurement of the magnetic and the electric fields would be necessary. Similar complexity affects the use of handheld devices, which are held close to the body.

On the other hand, if the general public is located in the antenna's radiating far field, the measurements are far simpler because the nature of the electromagnetic wave becomes predictable at those further distances.

It is your responsibility to take the necessary precautions to protect the safety of anyone who can be exposed to your station's emissions. If you are unable to perform the actual measurements, you should learn about the risks of overexposure and how they are influenced by the design of your station, especially by your antenna, before commencing any transmissions. You should also study the ICNIRP guidelines so that you can make your own, responsible decisions.[368]

For the purposes of the exam, you do not need to memorise the ICNIRP guidelines. You are required, however, to know:

- that you must follow the ICNIRP guidelines,
- the types of risks,
- station characteristics that influence emissions,
- how to take basic exposure precautions.

19.8.3 Nature of the Risks

The primary ADVERSE EFFECT of RF EMF exposure is the heating of human tissue. Just like a microwave oven can cook food, sufficiently high intensity radio waves will heat your eyes, brain, body etc. Heating of body tissue by RF EMF is a particular risk if the heat cannot be dissipated quickly enough by the body's natural cooling mechanisms. The ICNIRP guidelines take a conservative view on the matter and stipulate several sets of protective exposure limits.

367 Measurements must be unperturbed, which means that the presence of the person making the measurements, or even some of the measuring equipment, would affect the measurements and therefore render them incorrect. ITU, IEC (International Electrotechnical Commission), and IEEE publish detailed specifications how to perform the measurements.

368 While you have a legal duty of care to other persons, the law and the guidelines do not make statements about the risks you may wish to expose yourself to. Seek further legal advice if in doubt. As mentioned in the disclaimer at the beginning of this document and at the start of this section, neither the authors of this guide, nor the IRTS take any responsibility for the quality, or the appropriateness of the advice contained in this study guide.

The most hazardous biological effect of RF exposure is an RF burn. See section 19.3.2 RF Burns from Direct and Near Contact with RF Currents. As a general practice, never touch antenna elements or other conductors unless you are confident that they are not energised.

! To avoid the risk of touch hazard, ensure no part of your antenna is closer to, or lower than 2.4 m above the level on which people can stand.

Eyes may be quickly damaged through heating by a high RF power density, especially at microwave frequencies.

! Never look inside an active waveguide or stand close in front of an active microwave antenna.

A second adverse effect that the ICNIRP guidelines are concerned about is the ability of RF at frequencies up to 10 MHz to induce currents in the nervous system that might result in electrostimulation.[369] Generally, for typical amateur radio installations, such effects are not likely without a physical contact.[370]

It is relatively easy to ensure only very low levels of emissions, for example, by using a low power transmitter feeding a large antenna, such as a half-wave dipole, that is located far from anyone. However, it is equally easy to exceed the limits by using a high-power transmitter, or an amplifier, feeding an antenna close by, including a magnetic loop antenna, a high gain multi-element Yagi, or a parabolic dish, especially a *small* one. The small size of some antennas can offer a false sense of security. Because the energy is initially concentrated near the antenna, their proximity and small size can yield surprisingly intense fields.

In that last case, even a short-term presence of a person's head in front of the antenna could cause ICNIRP exposure limits to be exceeded with moderate levels of power.

Particular care needs to be taken when using magnetic loop antennas. Their small size can be deceptive considering the strength of the fields at the close distances where they are sometimes used.[371]

Health-related risks other than RF exposure causing heating of the body tissue have not been sufficiently demonstrated in scientific research yet. Further studies

369 Human nerve cells are electrical conductors. It is assumed that if they are subjected to a strong field a current can be induced in them, which, if excessive, could have a detrimental effect on the functioning of the nervous system.

370 The dominant frequencies for shock effects are below 100 kHz and are usually associated with pulsed fields having very narrow pulse widths. Those frequencies are not common in amateur radio.

371 Be careful where you locate any indoor antennas, especially if considering out-of-sight areas such as an attic space. High quality magnetic loop antennas may cause intense heating of nearby conductors, even when fed with only moderate amounts of power. Ensure good electrical and fire safety.

have been conducted.[372] The European Commission Final Opinion on EMF which was published in 2015 states: [373]

- *The results of current scientific research show that* there are no *evident adverse health effects if exposure remains below the levels recommended by the EU legislation. Overall, the epidemiological studies on radiofrequency EMF exposure* do not *show an increased risk of brain tumours. Furthermore, they* do not *indicate an increased risk for other cancers of the head and neck region. Previous studies also suggested an association of EMF with an increased risk of Alzheimer's disease. New studies on that subject* did not *confirm that link.*

A similar assessment of the lack of clear scientific evidence regarding some other risks can be found in the 2020 ICNIRP guidelines, appendix B.[374]

Some medical devices, including cardiac pacemakers, may be affected by a strong EMF. This is more likely to be a concern if the individual is close to the antenna. Although modern medical devices are designed with awareness of the widespread use of mobile phones, users should always seek guidance from their medical professional on what actions, if any, they need to take with respect to RF EMF.

19.8.4 Station Characteristics Influencing RF Emissions

You must understand the key characteristics of your station that you can control that have a direct impact on the level of RF emissions from it.

- Power supplied to the antenna will directly influence the emissions from it. Depending on the type and the length of the transmission line there may be a significant loss of power before it reaches the antenna, see section 14.2 Line Loss (Attenuation). Bear in mind that compliance with your licence power limits (Table 25-C) does not guarantee compliance with exposure limits.
- Antenna characteristics, especially antenna gain and its radiation patterns, determine the emissions from it – see section 15.15 Directivity, Efficiency, and Gain.
- The EMFs surrounding an antenna greatly depend on its physical design and on the distance from it. Broadly, there are two regions surrounding the antenna that must be considered separately in terms of exposure limits: the near and the far fields, see

372 A new consultation on the need for a revision to the ICNIRP guidelines has been conducted in 2022-2023. It has concluded that the guidelines do not need to be amended, however, it recommended further, scientific studies. See health.ec.europa.eu/system/files/2023-06/scheer_o_044.pdf.

373 ec.europa.eu/health/other-pages/health-sc-basic-page/final-opinion-emf_en

374 ICNIRP 2020 Guidelines Appendix B discusses the *lack of clear scientific evidence* linking radio frequency exposure and the following other risks that were subject of studies: *brain electrical activity and cognitive performance; mood and behaviour; auditory, vestibular, and ocular function; neuroendocrine system; neurodegenerative disease; cardiovascular system, autonomic nervous system, and thermoregulation subject to the observance of the guideline limits; immune system and haematology; fertility, reproduction, and childhood development, except for the thermal effects that are subject to the guideline limits; cancer.* Although there was a lack of clear evidence for those risks, further studies are continuing.

section 15.2 Near and Far Antenna Fields. The power supplied to the antenna determines how strong those differently shaped EMFs are in those regions.

- The antenna's near field pattern, especially the *reactive* near field can be quite different from the antenna's far field pattern – see examples in the figures below. EMFs in the near field region can be greatly influenced by the presence of structures such as a house, wire fence, reflections from the ground etc. They are difficult to predict in most real-world situations. Be aware that RF exposure calculators based only on far field assumptions may be inaccurate or misleading for predicting exposure in the near field. For example, a magnetic loop antenna has a deceptively small size, but its strong near reactive field can extend surprisingly far from it. As a rule of thumb, avoid the presence of people in the near reactive field when an antenna is in use.
- The emissions in the far field of an antenna can be more easily estimated from the antenna's EIRP in a given direction, see section 15.20. The far field radiation patterns are well understood and can be predicted using calculators, modelling software, and ready-made guides. They determine the location and the distance of the people from the antenna where overexposure might occur. A multielement Yagi, or a parabolic dish will have a much narrower, more focused radiation pattern than a half-wave dipole or a vertical quarter-wave antenna. You need to consider if people may be present directly in front of the beam – something that is unlikely if those antennas are mounted on a mast at a sufficient height.

For example, Figure 19-ii shows the patterns of electric field strength from an 8-element 144 MHz Yagi antenna, mounted 8 m above ground, using 400 W average power.[375] There are areas, under the antenna, not immediately close to it, where the exposure of a person standing there might exceed the ICNIRP limits during transmissions. At the same time, beyond about 25 m from that antenna, the emissions are unlikely to cause any excessive exposure.[376]

Compare to the same antenna fed with only 50 W average power, in Figure 19-iii. There is no location on the ground, neither near nor far from the antenna, where the exposure limits would be exceeded. However, if you were to stand on the tower, immediately next to the antenna, or on a ladder, roof, or balcony in front of it up to about 7 m away, you could still be exposed in excess of some of the limits.

375 Averaged power means rms power in this context. It is generally not the same as PEP (Peak Envelope Power) that is used to define regulatory power output limits. The type of modulation must be considered to convert PEP to averaged power. However, averaged power is more appropriate for safety evaluations because it is more directly related to the energy that may be absorbed by the body in a period of time.

376 These exposure patterns required a large set of detailed antenna calculations to identify all the regions, on the ground and in the space, within which the *spatially averaged* field may exceed the relevant ICNIRP guidelines. Advanced EMF modelling software and mathematical techniques were used to calculate them. This work was published by the RSGB EMF team, see page 309.

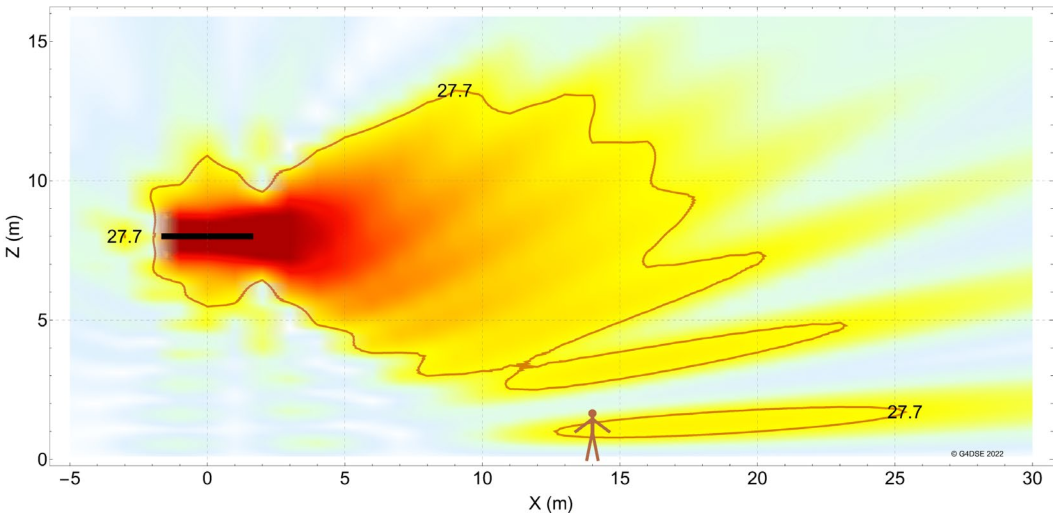

Figure 19-ii: Electric field strength pattern of an 8-element Yagi antenna fed with 400 W averaged power at 144 MHz. Contour line shows 27.7 V/m ICNIRP exposure limit applicable at this frequency. Height on the vertical, distance on the horizontal axis. [Image by Peter Zollman. See 375]

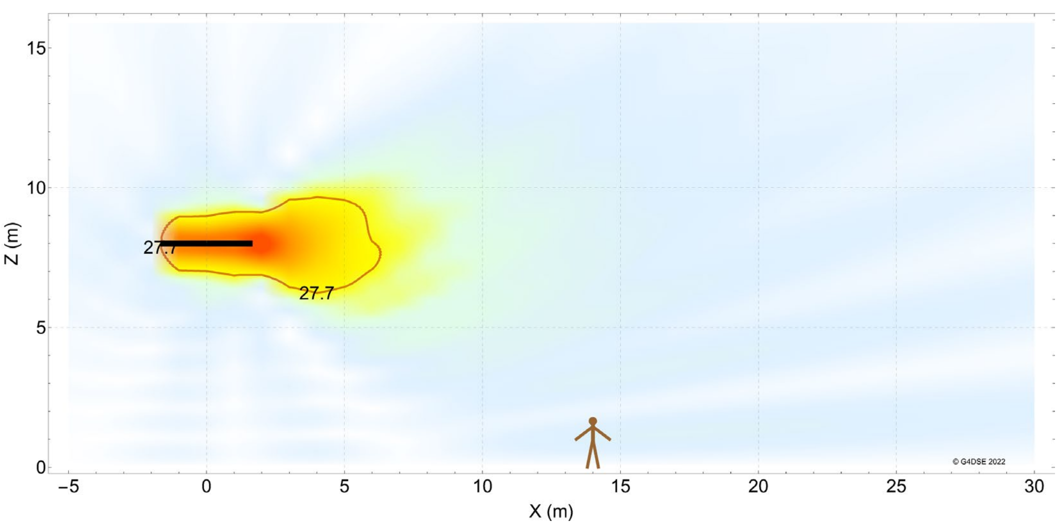

Figure 19-iii: Electric field strength pattern of an 8-element Yagi antenna fed with 50 W average power at 144 MHz. Contour line shows 27.7 V/m ICNIRP exposure limit applicable at this frequency. [Image by Peter Zollman, see page 375]

19.8.5 Estimating and Modelling RF Field Strengths and Exposure

In free space, the intensity of the fields reduces as the distance increases. In the far radiating field, field intensity halves as the distance doubles. Formulae for estimating field strengths, and the ICNIRP guide can be used to predict if the emissions are likely

to exceed the exposure limits in the far field.[377] Unfortunately, similar calculations for the near fields are more complex. They require advanced antenna modelling, and a careful interpretation of ICNIRP standards. Calculations need to include reflections from ground. It is also difficult to include the effects of obstructions such as nearby buildings or trees. Nevertheless, modelling provides insight into EMF compliance for an amateur station.

For example, compare the well-known toroidal far-field emission pattern of a half-wave dipole in Figure 15-v to its near field emission patterns shown in Figure 19-iv. Further, as expected from Figure 15-iii, the electric field is strongest near the ends of the antenna where the voltages are highest, while the magnetic field is strongest at the centre, where the current is highest.

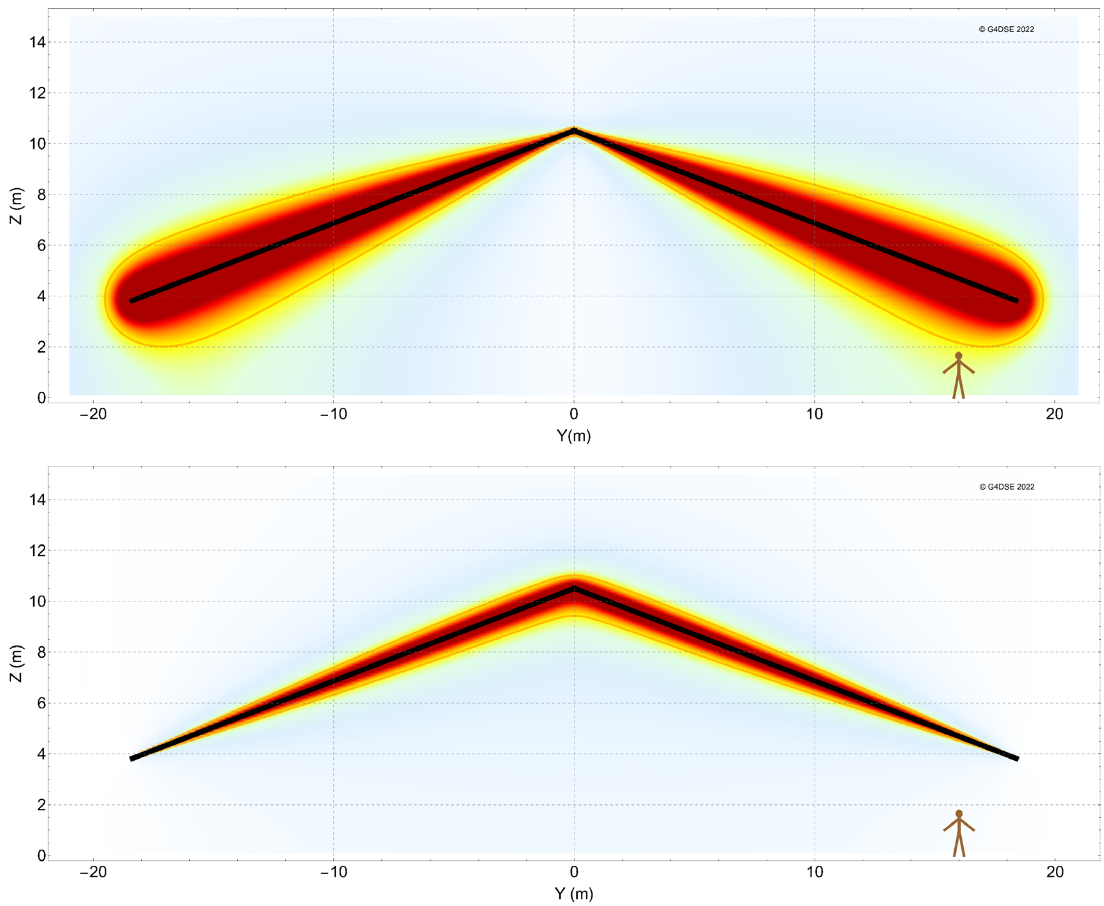

Figure 19-iv: Electric field strength (above) and magnetic field strength (below) near to an inverted V half-wave dipole fed with 400 W average power at 3.650 MHz. Contour line shows 83 V/m ICNIRP exposure limit applicable at this frequency. [Image by Peter Zollman, see page 375]

377 If d is the distance in metres from the antenna in the *far radiating field*, and EIRP is the *effective isotropic radiated power* in watts in the direction of interest, then the field strength in V/m can be estimated as: $Field\ Strength = \sqrt{(30 \times EIRP)}/d$. See also 15.20.1.

You should familiarise yourself with exposure limit calculators and guidelines published by other European users of the ICNIRP guidelines. For example, the Radio Society of Great Britain (RSGB) publishes an online calculator that estimates the minimum distances from an antenna at which the exposure is within guideline limits. See rsgb.org/emf.

Consider reviewing the *RSGB EMF Pre-Assessed Equipment Configuration* (PAEC) guides which explain, in detail, which configurations are likely to be compliant and which may require additional care. Available at rsgb.org/emf:

- PAEC-1: Half-wave dipoles (160m to 40m)
- PAEC-2: Rotatable Beam Antennas for 50 MHz to 1.3 GHz

Those guides offer practical observations. For example, a half-wave dipole, including inverted-V, operated on the 40–160 m bands is likely to be compliant with the ICNIRP exposure guidelines when fed with *average* power up to 400 W if:

1. It has been mounted at least 6.4 m above most kinds of ground (excluding high-conductivity ground such as salt marsh), and,
2. no person can remain closer to any part of the antenna than 2.2 m when transmitting.

The same half-wave dipole would require lesser precautions when operated with no more than 100 W average power.[378] The conditions would only require that:

1. It has been mounted at least 3.7 m above most kinds of ground (excluding high-conductivity ground such as salt marsh), and,
2. no person can remain closer to any part of the antenna than 1.2 m when transmitting.

Furthermore, in the case of the above two half-wave dipoles, the emissions in the far field would comply with the ICNIRP exposure guidelines.

Consider the above distances when thinking about other antenna configurations, for example if designing an antenna for the interior of your house, attic, or when using physically smaller antennas, especially inside an apartment – the necessary distances may be larger than the circumstances suggest.

Another consideration is how long any potentially exposed person can remain where they should not be according to the models or measurements. Someone walking past such a location, or a mobile station in a moving car, would yield a reduced exposure to the public. On the other hand, if the vehicle were stationary, or if passers-

378 Use the EMF online calculators, such as rsgb.org/emf, to find the average power of different communication modes. To calculate the *average power,* the PEP is multiplied by two further factors: the mode factor, and the operational duty factor, see section 12.2 for an explanation. Assuming 100 W PEP, transmission for 50% of the averaging period, the *average* power would be: 10 W for typical, uncompressed SSB, 25 W for typical, compressed (processed) SSB, 50 W for FM and AM, 20 W for typical CW, and 50 W for RTTY and FSK. For FT8 and FT4, the transmit/receive duty cycle is fixed, and part of the mode factor. The average power in this case would be 42 W for FT8, no matter how lightly or intensively the operator uses it. In all of those cases, the *peak* power remains 100 W.

by could stop for longer periods, then the operator would have to be aware of the risk and operate in a way to mitigate it.

Although modelling and estimation do not replace real-world, accurate, calibrated measurements, even considering the difficulty of measuring emissions in the near fields, studying the models and guidelines can provide you with sufficient information to judge your site and to make well-informed decisions about the design of your station. You should consider all those aspects as part of your overall station safety awareness.[379]

19.8.6 Interior of Transmitters and Power Amplifiers

There are strong EMFs inside high power solid-state and valve transmitters and amplifiers. High power valve amplifiers generally involve high DC and RF voltages. In addition to the significant electric shock hazards, they generate large RF electric fields. High power solid-state amplifiers operate at lower DC voltages, but instead they use very high RF currents which generate large RF magnetic fields. Safety is normally provided by the grounded metal case in which the device is housed.

! Unless absolutely essential, do not operate transmitters and amplifiers while their RF shielding covers are open.

It is rarely necessary, and not a good practice because some equipment may not function correctly without the shielding. Always remember to return all shields into place and close all covers and cases before returning it to use.

19.8.7 Practical Suggestions

While you are responsible for ensuring the safety of people who can be affected by your station, at the same time, you are entitled to enjoy the full benefits of your licence. The Irish amateur station licence allows the use of a full transmit power, in line with the regulatory limits, which are summarised in Table 25-C on page 343. There is no reason you should not benefit from this entitlement, as long as you can avoid exposing people in excess of the ICNIRP guideline limits.

Until you have gained more experience, and whilst designing your first station, consider using well-tested, widely used equipment and antenna configurations that have stood the test of time, such as a simple half-wave dipole, high enough above the ground, and keep power as low as practical for communications.

EMF compliance and good EMC management (Chapter 18) go together. If in doubt, follow these simplified guidelines, bearing in mind that in some situations they may be overcautious, but in others they may be insufficient. It is your

379 Accurate, calibrated measurements are the preferred means of establishing compliance according to COMREG publication 21/90 *Proposed Strategy for Managing the Radio Spectrum 2022 to 2024*, in which COMREG stated its *preliminary view that measurement of sites is necessary to guarantee compliance with limits and to-date [ComReg] has not accepted modelling as an alternative.*

responsibility to apply this summary advice in a manner appropriate to your situation, and always in line with the ICNIRP guidelines.

- Keep the power as low as is necessary to maintain compliance, and always within the regulatory limits.
- Site antennas as high and as far away from people as practical.
- Understand where the intense near field of your antenna is likely to be and avoid allowing people into that region when you are transmitting.
- Be aware that the size of some antennas, such as magnetic loops, may be deceptively small considering the much larger size and the intensity of their near field.
- Ensure that the ends of inverted-V dipoles and doublets are elevated and always out of reach.
- Control the access to ground-mounted vertical antennas to avoid the risk of anyone touching them when in use.
- If using high-gain, directional antennas, such as Yagis or parabolic dishes, ensure no one can be present in front of the beam, especially if not mounted high enough, even if using moderate levels of power.
- Avoid using hand-held or body-worn devices with antennas close to the head or body at RF power levels above 5 W. [380]
- Do not operate transmitters or amplifiers with their cases or covers open.
- Consider the general public when operating field days. Ensure their safety and be prepared to knowledgeably discuss EMF safety.
- Always consider the concerns of your neighbours and be prepared to explain to them the steps that you have taken to ensure EMF compliance, for example: by siting your antenna high and far enough, by preventing access to it, and by operating with levels of power and duration that could not cause any overexposure at their location.

It would be prudent to prepare yourself for a possible discussion about matters of radio safety with others, who may not be familiar with the technical aspects of how your radio station and antennas work. RSGB offers a guide at rsgb.org/emf

- *EMF-3 Communicating with Neighbours and General Public about EMF Compliance*

380 Beware of handheld devices without CE type approval. It means an untested product, or a failed test. Power levels and EMFs may exceed regulatory safety levels. As a licensed radio amateur, you are allowed to use devices without the CE mark if *you* accept the overall responsibility for people safety.

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Part B:
Operating Rules, Procedures and Regulations

20 ITU Radio Regulations

TWO EXAM QUESTIONS · SECTION B8

20.1 International Telecommunications Union (ITU)

The International Telecommunication Union (ITU) is the United Nations (UN) agency for information and communication technologies. The ITU RADIO REGULATIONS govern the legal and technical requirements of all users of radio frequencies, whether they be government, commercial, amateur or any other group. The four volumes are freely available to download.[381] This chapter summarises the key ITU regulations that affect Irish radio amateurs.

20.2 ITU Radio Regions and the IARU

The ITU has divided the world into three REGIONS for administrative purposes.

- REGION 1: Europe, Africa, the former Soviet Union, Mongolia, the Middle East west of the Persian Gulf including Iraq.
- REGION 2: Americas including Greenland, and some eastern Pacific Islands.
- REGION 3: Asia east of and including Iran but excluding former Soviet Union, and most Oceania (Australia and New Zealand).

The INTERNATIONAL AMATEUR RADIO UNION (IARU) is the worldwide representative body for amateur radio and is organised in three similar Regions.

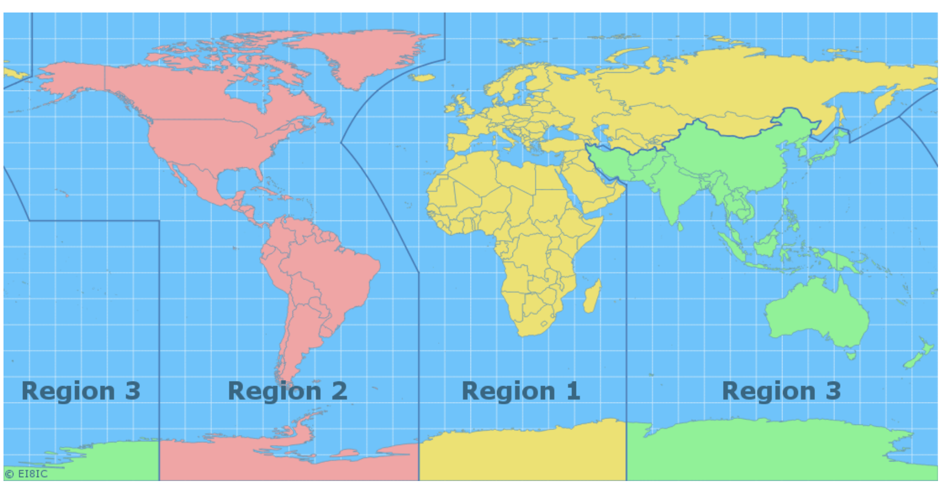

Figure 20-i: Map of the IARU regions. [Image by IARU, see page 375]

381 www.itu.int/pub/R-REG-RR

The IARU represents the interests of radio amateurs worldwide by working closely with and participating in ITU decision making processes, notably to protect the immensely valuable amateur radio spectrum from being irrevocably lost to the demands of commercial interests. In turn, the Irish Radio Transmitters Society (IRTS) is Ireland's representation within the IARU R1. The most important function of the IRTS has always been to represent the interests of Irish radio amateurs to protect and to grow our worldwide rights, by working internationally, through the IARU, and nationally, with Commission for Communications Regulation (ComReg) and with other Irish organisations.

20.3 Purpose of the Amateur Service

The ITU radio regulations define the AMATEUR SERVICE as a radio communication service for the purposes of:

- self-training
- intercommunication
- technical investigations

... carried out by amateurs, that is, by duly authorised persons interested in radio technique solely with a PERSONAL AIM and without PECUNIARY INTEREST.[382]

20.4 Permitted Communications

Radio Regulations state that radio communication between amateur stations[383]

1. in different countries is permitted unless the administration of one of the countries concerned has notified that it objects to such radio communications
2. is limited to communications incidental to the purposes of the amateur service and to remarks of a personal character
3. cannot be encoded for the purpose of obscuring their meaning, except for control signals exchanged between earth command stations and space stations in the amateur-satellite service.

For ordinary communications, Morse Code can be used, as can any other form of encoding, such as computer-generated digital modes, provided the form of encoding is not secret.

In general, licensed amateur stations are permitted only to contact other licensed amateur stations in Ireland and abroad.

This restriction, and the restriction on the content of transmissions mentioned in point 2 above, may be eased for communications in case of emergencies or disaster

382 It means that you cannot make money from amateur service radio communications.
383 ITU Radio Regulations, articles 25.1, 25.2, and 25.3.

relief. In line with the ITU guidelines, ComReg encourages radio amateurs to provide a means of communications during emergencies or natural disasters.

An example of an Irish amateur radio emergency communications organisations that provides these types of emergency communication is the AMATEUR RADIO EMERGENCY NETWORK. AREN is a public service voluntary radio emergency network. It is run by the IRTS in co-operation with ComReg. AREN operators are permitted to pass messages of designated services, including the Ambulance Service, Civil Defence, Fire Service, An Garda Síochána, Health Services Executive, Irish Coast Guard, Mountain Rescue, Irish Red Cross, and the voluntary ambulance services. See also section 27.4 Role of Licensed Radio Amateurs in Emergency Communication.

20.5 Primary and Secondary Allocations

Frequency allocations are made by the ITU on a primary or secondary basis, in effect, determining the priority of the individual radio services. ComReg licences radio amateurs to operate within these specified frequencies, in Ireland, and on some frequencies, also in Irish territorial waters.

Most of the amateur bands within the scope of the exam syllabus are allocated on a PRIMARY basis.[384] It means that radio amateurs have priority use of those bands and can claim protection from harmful interference from secondary users.

Four of the amateur bands within the scope of the exam syllabus, 5 MHz, 10 MHz, 50 MHz, and 70 MHz, are allocated on a SECONDARY basis. The radio regulations specify that stations with a secondary allocation:

- shall not cause harmful interference to stations of primary services
- cannot claim protection from harmful interference from stations with a primary allocation.

20.6 Emission Designators

The ITU uses an internationally agreed system for classifying radio frequency signals. Each type of radio emission is classified according to several factors which describe the characteristics of the signal – not the transmitter used.

National regulations refer to these emission designators to specify which types of transmissions are permitted on which frequency bands in Ireland. The designators are also used to remove ambiguity when discussing similar types of signals, for example, to differentiate between various types of amplitude modulated signals.

This classification, referred to as the ITU EMISSION DESIGNATORS, has a minimum of three characters, for example, J3E. Each of the three symbols has the following meaning: type of modulation, nature of modulating signal, type of information transmitted.[385] The most common designators are listed in Table 20-A. All

384 Some of allocations are on a *primary shared* basis – shared with other non-amateur primary users.
385 See ComReg document 08/34, www.comreg.ie/media/dlm_uploads/2015/12/ComReg0834.pdf.

the modes mentioned in the table are explained in detail in Chapter 11 Modulation and Modes.

Table 20-A: Common ITU emission designators

TYPE OF MODULATION	
A	Amplitude modulation, double sideband
J	Amplitude modulation, single sideband, suppressed carrier
F	Frequency modulation
G	Phase modulation
NATURE OF MODULATING SIGNAL	
1	One channel containing digital information, no subcarrier
2	One channel containing digital information, using a subcarrier
3	One channel containing analogue information
TYPE OF INFORMATION TRANSMITTED	
A	Aural telegraphy, intended to be decoded by ear, e.g., Morse Code
B	Automatic (machine) reception telegraphy (RTTY, FT8, PSK31)
D	Data, e.g., computer files, telemetry, packet radio [386]
E	Telephony (phone) voice
The most common emission designators	
A1A	CW (Morse code telegraphy using on-off keying of the carrier)
J3E	SSB (single side band amplitude modulation, suppressed carrier, speech)
A3E	AM (amplitude modulation with both carriers, speech)
F3E	FM (frequency modulation, speech)
F1B, F2B, J2B	RTTY, AMTOR, FT8 (telegraphy)
F1D, F2D, J2D	Packet radio, files, telemetry, and computer data
G1B, J2B	PSK31 (telegraphy)

386 The difference between telegraphy XXB and data XXD can be fuzzy. B refers to textual information, such as *Hello John, how are you?*, while D refers to data transmission, telemetry or telecommand (remote control). In the past, B used to be immediately seen without further processing, on a teleprinter. D required additional, computer-based processing. Nowadays, computers are used for both. Should textual information using a mode such as RTTY or FT8 be designated as B or D? In general, B should designate textual, human-readable content, while D everything else.

20.7 Frequency of Identification

The ITU Radio Regulations require all radio transmissions to be identified:

! During the course of their transmissions, amateur stations shall transmit their call sign at SHORT INTERVALS.[387]

However, there are further Irish regulations and IARU operating procedure guidelines about how often the transmissions should or must be identified. The additional requirements state that:

- You should identify yourself at the start and at the end of each transmission, and you must identify yourself at frequent, short intervals.
- If operating from a land mobile or maritime mobile station, you must identify at the start and at the end, or at intervals of 30 minutes whichever is the more frequent.

When travelling abroad in international waters the rules of other countries and regions apply and they can differ greatly from those in Ireland. General rules when operating abroad are covered in the next chapter.

387 ITU Radio Regulations section 25.9 in the 2020 and prior editions.

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21 CEPT Regulations

THREE EXAM QUESTIONS · SECTION B9

21.1 CEPT and HAREC

CEPT stands for The European Conference of Postal and Telecommunications Administrations. It is a European organisation where policy makers and regulators collaborate to harmonise telecommunication, radio spectrum, and postal regulations. CEPT works closely with the ITU and the IARU. Two areas of CEPT work have been of significant benefit to radio amateurs.

1. Arrangements which make it possible for radio amateurs from CEPT countries to operate during short visits to other CEPT countries without obtaining an individual temporary licence from the visited CEPT country. These arrangements are described in CEPT ELECTRONIC COMMUNICATIONS COMMITTEE (ECC) Technical Recommendation (T/R) 61-01.[388]
2. The HARMONISED AMATEUR RADIO EXAMINATION CERTIFICATE (HAREC) which enables radio amateurs who have successfully passed a HAREC-standard exam in one country to obtain a licence in another country. The ComReg Irish exam complies with this standard. Once you pass it you will receive a HAREC certificate from ComReg which you can use to obtain a licence in other participating countries in which you have a permanent address. The HAREC standard is defined in CEPT ECC recommendation T/R 61-02.[389]

A small number of countries have not adopted recommendations T/R 61-01 and T/R 61-02. Some countries have only adopted one.[390] Figure 21-i on the next page shows a map of European countries which have implemented T/R 61-01. There are a few more countries, outside of Europe, which have also implemented this CEPT recommendation, incl. Canada and the USA.[391]

21.2 CEPT Radio Amateur Licence

Both CEPT Class 1 and CEPT Class 2 Amateur Station Licences issued by ComReg in Ireland (see 22.3 Obtaining an Irish Amateur Station Licence) are considered to be equivalent in terms of the CEPT recommendation T/R 61-01. They are both CEPT licences. A CEPT licence permits you to operate in another country which has

388 docdb.cept.org/document/925
389 docdb.cept.org/document/926
390 The USA has only adopted T/R 61-01, giving an Irish CEPT licence holder the right to operate there as a visitor. However, they have not adopted T/R 61-02 meaning the HAREC could not be used to obtain a permanent American amateur station licence.
391 CEPT only makes recommendations, aimed at national telecommunication agencies, like COMREG. It is up to each country to decide to disregard or to adopt them into the national laws and regulations.

implemented CEPT recommendation T/R 61-01 during a short visit, without having to obtain a temporary or a visitor's licence. However, it is a requirement of the CEPT licence that you must learn about and strictly observe the regulations of the country you are visiting in addition to observing the limits of your own licence. For example, if the country you are visiting recognises CEPT licences, but its regulations do not permit the use of certain frequencies, or the power limits are different than in Ireland, you must not use those frequencies and you must obey the power limits of the country you are visiting.

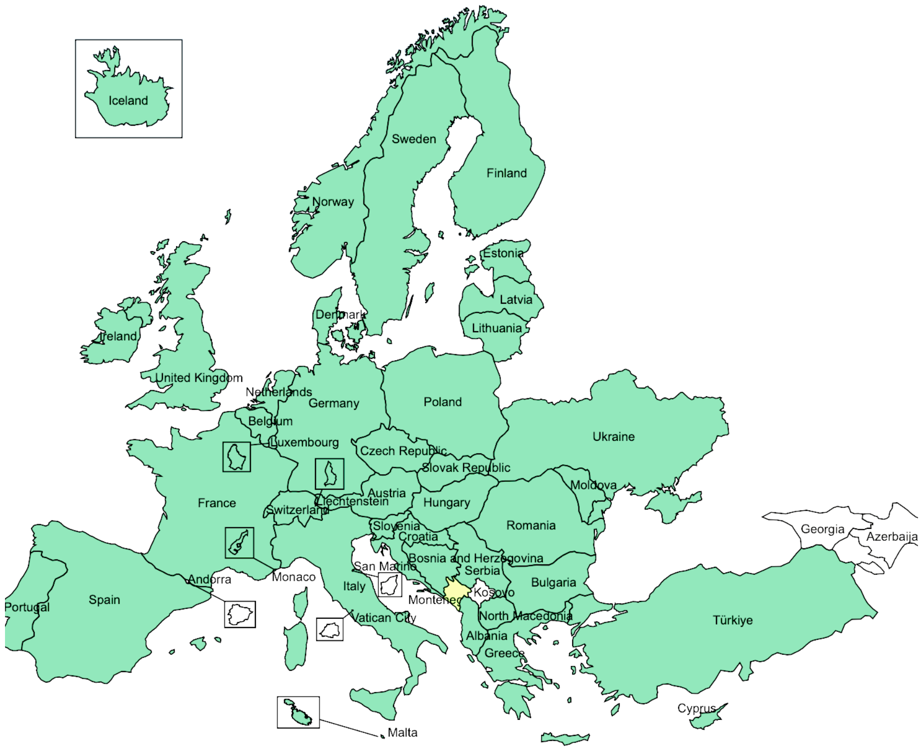

Figure 21-i: European countries which have implemented recommendation T/R 61-01 are marked green on this map. You can operate there using your Irish CEPT licence during short visits without obtaining a temporary licence. Non-CEPT countries which have implemented it include Australia, Canada, Israel, New Zealand, Peru, South Africa, and the USA.[392] [Image by ECO, see page 375]

You must always check with the regulator of the country that you are planning to visit to see if the CEPT arrangements are in place and if there are any special requirements that you must fulfil. You should also consult the IARU R1 *Operating Abroad* guide.[393]

In most countries, the CEPT licence is equivalent to the highest amateur station licence, subject to several conditions.

392 Map current as of January 2024. See docdb.cept.org/implementation/925/map.

393 www.iaru-r1.org/reference/operating-abroad. The German radio society DARC also maintains a comprehensive list of licence privileges, frequencies, and permitted power levels, in CEPT agreement signatory countries. See files.darc.de/index.php/s/CKT38kZP6miK7xf.

1 These arrangements are valid only for non-residents for the duration of their SHORT TEMPORARY VISIT. The duration is defined by each country, usually up to 3 months.
2 Regulations, frequencies, modes, and power limits that are in force for the national CEPT-equivalent licence in the COUNTRY BEING VISITED must be observed.
3 Technical and operational restrictions imposed by national, local, or public authorities must be respected.
4 Protection against harmful interference cannot be requested by the visitor.

A small number of countries may still afford a holder of an Irish CEPT Class 1 licence additional operational privileges when visiting that country in addition to the provisions of T/R 61-01. To know what they are you need to research the regulations of the country you plan to visit.

21.3 Prefix When Visiting a Country Implementing CEPT T/R 61-01

The visitor must use their own call sign preceded by the CALL SIGN PREFIX of the visited country, with the character / spoken as *stroke* or *slash* separating the prefix from the call sign.[394] The national prefix that you must use when visiting another CEPT signatory country is specified in T/R 61-01. For example:

- Irish visitor to Denmark: OZ/EI5ABC
- Irish visitor to Northern Ireland: MI/EI5ABC
- Danish visitor to Ireland: EI/OZ5ABC

Many islands require the use of a prefix that may be different to that of the island's country.[395] This applies to Ireland, too. CEPT licensees visiting Ireland use EI/ when operating on the mainland, but EJ/ when operating from Irish offshore islands, such as the Aran Island of Inishmore.

Bear in mind that an Irish mainland licence holder, such as EI0SWL who is visiting an Irish offshore island simply changes their call sign to EJ0SWL, and the other way round. As an Irish call sign holder, do not prefix your Irish call sign with the EJ/ or EI/ prefixes containing a slash. Those are reserved for licensees from other CEPT countries who are visiting Ireland. See also 24.3 Irish Call Signs.

Some countries require the visited country's call sign prefix to be followed by a number or a letter indicating the region where the station is operating, or a prefix which is specific to the state or a province, like in USA or Canada. They are known

394 The *IARU Ethics and Operating Procedures Guide* recommends that you pronounce it as *stroke,* which is what you are likely to hear on the air, unless communicating with a station in US or Canada, where the word *portable* is used for this purpose. Some COMREG guidelines prefer *slash.*

395 For example, Portugal uses CT7/ but when visiting Madeira you would prefix CT9/. France uses F/ but when visiting Corsica, you would prefix TK/. Refer to CEPT document 61-01 Annex 2 for the full list.

as REGIONAL INDICATORS.[396] When visiting countries that use regional indicators you should use them, even if they are not shown in T/R 61-01, unless the country makes regional indicators optional for visitors.

For example, when visiting England, you use M/ (not G), in Northern Ireland MI/ (not GI), MM/ in Scotland, and MW/ in Wales – even though other prefixes, such as 2E or G, GI, GM, and GW also denote those countries.

21.4 National Call Sign Prefixes

Call sign prefixes identify the country, and sometimes the region and licence class, of the operator. There are hundreds of prefixes in common use.[397] Exam candidates are expected to know the principal call sign prefixes used in Europe, Canada, and the USA, which are the prefixes that must be used when visiting those countries with an Irish CEPT licence. Always check the regulations of the country visited to make sure you are correctly using your call sign, prefix, and any regional indicators.

5B	Cyprus	OE	Austria
9A	Croatia	OH	Finland
9H	Malta	OK	Czechia
CT7	Portugal	OM	Slovakia
DL	Germany	ON	Belgium
EA	Spain	OZ	Denmark
EI, EJ	Ireland	PA	Netherlands
ES	Estonia	S5	Slovenia
F	France	SM	Sweden
HA	Hungary	SP	Poland
HB9	Switzerland	SV	Greece
I	Italy	TF	Iceland
LA	Norway	UA	Russia
LX	Luxembourg	UT	Ukraine
LY	Lithuania	YL	Latvia
LZ	Bulgaria	YO	Romania

Table 21-A: National prefixes: selected European countries

396 When visiting the USA you would prefix your call sign with the region-specific prefix, e.g. W9/EI5ABC when visiting Illinois. However, when visiting Canada, you would *suffix* (add at the end) your call sign with the Canadian region-specific *prefix*, e.g., EI5ABC/VE3 when visiting Ontario. Somewhat confusingly, different rules apply for Canadians visiting USA, who instead of prefixing continue to use the Canadian approach of suffixing.

397 Countries routinely issue call signs with prefixes other than shown. Only the prefixes in the tables in this section need to be learned for the exam. Full list, including rare special occasion prefixes, is at rsgb.org/main/operating/licensing-novs-visitors/international-prefixes.

To comply with the CEPT regulations when visiting a UK entity, use the M prefix shown in the first column in Table 21-B, and not the G or 2 prefixes.[398]

MI	2I	GI	Northern Ireland
MD	2D	GD	Isle of Man
MJ	2J	GJ	Jersey
MM	2M	GM	Scotland
MU	2U	GU	Guernsey
MW	2W	GW	Wales
M	2E	G	England

Table 21-B: National prefixes: UK entities

Canada and the USA require use of regional indicators in addition to the prefixes shown in Table 21-C. Indicators for each state and province are listed in document T/R 61-01.

A K N W	USA
VE	Canada

Table 21-C: National prefixes: Canada and USA

398 The use of regional indicators is under review by the British regulator, Ofcom, as of January 2024.

(*This page left blank to match the numbering in the printed edition*)

22 Irish Laws, Regulations, and Licence Conditions

THREE EXAM QUESTIONS · SECTION B10

22.1 Wireless Telegraphy Regulations

The WIRELESS TELEGRAPHY (AMATEUR STATION LICENCE) REGULATIONS 2009 provide for the licensing and the regulation of amateur radio stations in Ireland.[399] This act places important legal responsibilities on any person holding an Irish amateur radio station licence. Most importantly, this act makes it a legal requirement to have utmost regard for any guidelines that may be issued and amended by ComReg. This act also legally requires you to observe good engineering practices.

Many of your responsibilities are outlined in this chapter. However, this study guide does not offer legal advice, nor can it be used as the source of legal or regulatory information. Seek advice from a qualified solicitor if in doubt and always refer to the sources of legal information, including the Wireless Telegraphy (Amateur Station Licence) Regulations 2009 act and the relevant ComReg, CEPT, and ITU guidelines, regulations, and publications. Remember than when visiting other countries, you must also obey their laws and regulations, which may differ from Irish.

22.1.1 Who Can Use Your Station?

Irish amateur station licences are issued to a LICENSEE, who is a person. The licensee is permitted to keep a station, or stations, at the addresses provided to ComReg. Those addresses, including their GPS coordinates, are shown in the licence. The Wireless Telegraphy act permits the licensee to operate and maintain their station.

Importantly, the Wireless Telegraphy act also permits any other individuals to operate the licensed station but only under the DIRECT SUPERVISION of the licensee. There is no requirement for those individuals to have their own licences. This provision enables any licensed amateurs to let UNLICENSED PERSONS, such as shortwave listeners or prospective amateurs, to operate and gain useful experience – whilst using the station under the direct supervision of the licensee. See also 22.5 Club Licences for further guidelines.

22.2 ComReg Amateur Station Licence Guidelines

The Commission for Communications Regulation (ComReg) is the statutory body responsible for the regulation of the electronic communications sector, including telecommunications, radio communications, broadcasters, and the

399 www.irishstatutebook.ie/eli/2009/si/192

postal sector. ComReg is also responsible for the regulation of amateur station licences in Ireland.

The ComReg document 09/45 AMATEUR STATION LICENCE GUIDELINES sets out many of the terms on which an amateur station must be operated, including the frequency bands, operating modes, and power limits, as well as technical and engineering requirements. You are legally required to comply with these guidelines. You are legally required to know and to use the most recent revision that is available.[400] Make sure to monitor ComReg publications to receive the newer versions when they are published.

Those ComReg guidelines form an essential part of the exam syllabus. You should download the Amateur Station Licence Guidelines 09/45 from, and you should review the ComReg web page related to Radio Amateur licences at:

- comreg.ie/?dlm_download=amateur-station-licence-guidelines
- comreg.ie/industry/radio-spectrum/licensing/search-licence-type/radio-amateurs-2

It is important to note that the Wireless Telegraphy Regulations and ComReg Guidelines do not exempt the licensee from having to comply with any other statutory requirements or obligations that may apply, for example, planning, electrical, or safety regulations. In other words, you always have to comply with all other laws and applicable regulations.

22.3 Obtaining an Irish Amateur Station Licence

ComReg issues Amateur Station Licences in Ireland. An amateur station licence permits the KEEPING AND OPERATION of an amateur radio station, using the frequency bands, modes and powers specified in the licence. These bands, modes, and powers would generally be those specified in Annex 1 of the ComReg Amateur Station Licence Guidelines 09/45.

- Your CALL SIGN, which you must use to identify yourself on the air, will be listed in the licence issued to you by ComReg.

To obtain an Amateur Station Licence, the applicant must successfully pass an examination to the CEPT ECC T/R 61-02 HAREC standard. The IRTS offers this exam in Ireland, however, a HAREC certificate issued in another CEPT country is also acceptable, thanks to CEPT recommendation T/R 61-01, which Ireland, like many other countries, has adopted. See 21.1 CEPT and HAREC.

The CEPT regulations do not require Morse qualifications. However, Irish regulations recognise Morse proficiency by offering two classes of licences. Both of those

[400] Revision R6 issued by ComReg on 29 May 2023 was current as of January 2024.

licence classes are equivalent in terms of the CEPT regulations set out in T/R 61-01. ComReg will issue a holder of a HAREC qualification with:

- CEPT CLASS 1 LICENCE if evidence of MORSE QUALIFICATIONS is provided
- CEPT CLASS 2 LICENCE if no evidence of the Morse qualification is provided.

Both licence classes have the same rights and entitlements in Ireland, except for a different type of a call sign. Class 1 licence call signs are shorter, see section 24.1 Allocation of Call Signs.

The IRTS conducts Morse proficiency testing to the standard required by ComReg to issue the CEPT Class 1 licence. See irts.ie/morse.

22.4 Licence Application, Duration, Amendments, Cancellation, Revocation

All applications for new or amended Amateur Station Licences must be made using the ComReg eLicensing website.

- www.elicensing.comreg.ie

If an applicant does not permanently reside in Ireland, full particulars of the Amateur Station, including contact details, station details and qualifications must be submitted. ComReg may only grant a licence for wireless telegraphy apparatus that is installed for use within Ireland. The address of the station must be an address in Ireland.[401]

All Amateur Station Licences, except for temporary assignments, are issued for the LIFETIME of the licensee. However, every 5 years, all licensees are required to confirm to ComReg that their licence details are up to date and correct, using the eLicensing website.

It is the responsibility of licensees to inform ComReg of any changes to the details relating to their licences, as granted, such as their address or contact details as soon as such changes occur, and no later than 28 days after they have occurred. An amendment to an Amateur Station Licences is required if the Amateur Station address changes because the details of the licence would need to be updated to reflect it. Any requests for changes to licence details should be made via the eLicensing website.

An Amateur Station Licence may be CANCELLED at the written request of the licensee. ComReg may SUSPEND or REVOKE an Amateur Station Licence where there is serious or repeated NON-COMPLIANCE by the licensee with the conditions of the licence. Licence fees will not be refunded in the event of cancellation or revocation of the licence.

401 COMREG does not issue licences to stations located in Northern Ireland. However, COMREG can issue a HAREC to a candidate who successfully passes the COMREG exam no matter where they live. That HAREC can be provided to Ofcom in the UK to obtain a UK licence in Northern Ireland.

22.5 Club Licences

A CLUB LICENCE is issued to a group of individual radio amateurs who have a common interest. An individual must be nominated to act as the NAMED LICENSEE on behalf of any club. Club licences will be issued in the name of such nominated individual. However, all rights and entitlements granted under a club licence, including any assigned frequency rights or call signs, shall vest in the club itself and not in the nominated individual holder of the club licence.

The nominated individual holder of the club licence, in addition to being the holder of the club licence, must also hold a valid Amateur Station Licence in their own name and must agree to be responsible for the operation of all radio equipment which is operated under the club licence.

22.6 Special Events

Many radio amateur clubs and individual licensees operate their stations to mark special events or occasions. These licensees may, on request, be issued with a special call sign for a temporary period, usually a couple of days and up to a year. Amateurs seeking such a special temporary call sign must apply via the eLicensing website at least one month before the event. The format of the special event call signs is discussed in section 24.1 Allocation of Call Signs.

22.7 Land Mobile

Where an amateur station is installed in a LAND-BASED VEHICLE the following additional provisions apply.

1 The call sign must be suffixed by /M, spoken as *slash mobile* according to regulations,[402] for example: EI5ABC/M
2 The particulars of the mobile station's location must be sent at the beginning and end of a contact with each station or at intervals of 30 minutes whichever is the more frequent.
3 A land mobile station cannot be established within any estuary, dock, or harbour or in the vicinity of an airport or radio navigation installation.
4 The power limit is 50 W (17 dBW), except on:
4.1 1 850–2 000 kHz band where the power limit is already lower at 10 W (10 dBW)
4.2 5 351.5–5 366.5 kHz band where the power limit is already lower at 15 W (12 dBW)
4.3 70 MHz band where the land mobile power limit is 25 W (14 dBW)

Please note that /M only applies to operation from a station installed in a *land-based vehicle*. It does not apply to operating from another address than the station's

402 The *IARU Ethics and Operating Procedures* guide recommends that you pronounce it as *stroke*. That is what you may hear on the air. COMREG guidelines 09/45 specify *slash*.

registered address, or whilst walking, or when setting up in a field, etc. It only applies to stations installed in a land-based vehicle.

Note that Irish regulations do not permit *portable* or /P call sign suffixes.[403] Unless in a land-based vehicle or a vessel, see next section, when operating away from the station's registered address you should always use your call sign, without any suffixes.

22.8 Maritime Mobile

An amateur station operating on water, whether at sea or on *any* waterway, river, or a lake, is considered to be a MARITIME MOBILE STATION, and is subject to the following additional provisions.

1. Approval to operate is required from the Ship's Master or owner, in all cases, including when in a harbour.
2. The call sign must be suffixed by /MM, spoken as *slash maritime mobile* according to regulations,[404] for example: EI5ABC/MM.
3. The particulars of the mobile station's geographic position must be sent at the beginning and end of a contact with each station or at intervals of 30 minutes whichever is the more frequent. Unlike land-based mobile, maritime mobile geographic position must be included in the *logbook* when recording communications.
4. The amateur station cannot be used for the sending or receipt of any message which would, if there were no amateur station on the vessel, be sent by means of the vessel's wireless telegraphy station.
5. The amateur station must not interfere with the wireless telegraphy station on the vessel. Should such interference occur, use of the amateur station must cease until the cause of the interference has been remedied.
6. Maritime mobile operation is *not permitted* on the 1.8 MHz, 5 MHz, 10 MHz, 50 MHz, 70 MHz, or 430 MHz bands, see also Table 25-C on page 343.
7. The power limit on all permitted bands is 10 W (10 dBW).

Licensed Irish amateurs or visitors, operating in Irish or in international waters, are subject to the conditions of their Irish licences and to all other laws to which the vessel, depending upon its location, is subject to. This means that you need to obey not only the conditions of your Irish licence, but also the rules of the country in which the vessel is registered, as well as the regulations related to the ITU region in which it is located when in INTERNATIONAL WATERS.

403 This is an example of an area where regulations and practice may differ. You will hear some operators use /P because that suffix used to exist in the Irish regulations. Unlike in Ireland, it still remains *optional* in some countries, for example in Germany, even if it is no longer required there.

404 The *IARU Ethics and Operating Procedures* guide recommends that you pronounce it as *stroke*. That is what you may hear on the air. ComReg guidelines 09/45 specify *slash*.

22.9 Logbook Keeping

A detailed LOGBOOK must be kept up to date at the amateur station and made available for inspection at the request of ComReg. The details to be included in the logbook are:

- date of transmission
- the times in UTC,[405] during each day of the first and last transmissions from the station and changes made to the frequency band, mode of emission or power
- frequency band of transmission
- mode of transmission
- power level (dBW or W)
- call sign of the licensed amateur station with which communications have been established.[406]

With the exception of *maritime mobile* operation, it is no longer required to log the geographic position of the transmissions in the logbook.

A practical logbook will include much more additional information, such as signal reports sent and received, the name and the QTH (location) of the person contacted,[407] notes about any requests, such as QSL (contact confirmations), and any other remarks. This additional information is not required by the regulations.

22.10 Additional Authorisations

Additional privileges or other licence types can be requested from ComReg. Formal application and authorisation is required for:

- additional frequency bands or power levels for experimental purposes
- automatic or remote station licence, for example, a repeater, beacon, or an Internet gateway.

22.11 Technical Requirements

The Wireless Telegraphy Act demands good site engineering practice in line with ComReg guidelines. Licence conditions include technical requirements to ensure:

1. no harmful interference is caused to other licensed services
2. the amateur station is constructed and maintained in such a manner as to ensure that the safety of persons or property is not endangered.

405 UTC stands for Coordinated Universal Time. It matches Irish winter time. It is one hour behind in the summer. In some countries it is known as GMT, Greenwich Mean Time, which UTC has succeeded.
406 It was formerly necessary to even log initial, unanswered calls, so-called CQ calls. This requirement has been removed in guidelines 09/45 R6, in contrast with revision R4.
407 See Chapter 26 Q-Codes and Abbreviations.

The licence conditions do not include detailed equipment specifications. A few broad requirements are listed:

1 Mechanical and electrical construction of the amateur station installation must be in accordance with best practice, see section 19.1 Radio Safety and The Irish Law.
2 All controls, meters, indicators, and terminals should be clearly labelled, see section 19.2 Equipment Labelling and Access Control Requirements.
3 The licensee must have a device capable of measuring SWR. See section 17.2 SWR and Power.
4 The licensee must also have an accurate method to ensure that operations take place on the correct frequency. In the case of home constructed equipment, a frequency counter or synthesised main receiver/transceiver would suffice. Commercially available equipment usually comes with an accurate frequency display. See section 17.7 Frequency Counter.
5 The licensee must ensure that non-ionising radiation emissions from their amateur station are within the limits specified by the guidelines published by the *International Commission for Non-Ionizing Radiation Protection* (*ICNIRP*). Your compliance with this aspect of safety is also a legal requirement laid out in the Wireless Telegraphy Regulations. See section 19.8 Non-Ionising Radiation and Electromagnetic Field Safety.
6 ComReg guidelines include limits for spurious emissions, also called spurious radiation, which vary according to frequency band and installation date of the transmitter. Please note that quantitative limits on spurious emissions are not within the scope of the exam syllabus. However, their aims must be understood. See section 18.2.1 Spurious Emissions.

22.12 CE Type Approval

When buying radio transmitting equipment, look for the CE TYPE APPROVAL MARK, see Figure 22-i. All radio transmitting equipment marketed or sold to the general public in Ireland and elsewhere in the EU must display CE marking.[408]

Figure 22-i: CE type approval mark [Public Domain]

To be allowed to place the mark on the product, the manufacturer must carefully test their radio equipment to ensure that it complies with the EU RED[409] and EMC directives,[410] and general electrical safety regulations required for all products sold within the EU.

408 More on CE marking at en.wikipedia.org/wiki/CE_marking and europa.eu/youreurope/business/product-requirements/labels-markings/ce-marking/index_en.htm.

409 Radio Equipment Directive 2014/53/EU, see ec.europa.eu/docsroom/documents/33162 and eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0053.

410 Electromagnetic Compatibility Directive 2014/30/EU, see eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0030.

Those EU directives require the manufacturer of radio equipment to certify that their device ensures:

- the protection of health and safety of persons and of domestic animals and the protection of property
- an adequate level of EMC
- that it both effectively uses and supports the efficient use of radio spectrum so as to avoid harmful interference.

However, as a licensed radio amateur you are allowed to build your own and to use equipment that DOES NOT HAVE THE CE MARK. This is a significant entitlement that comes from holding an amateur radio station licence. While the EU directive requires amateur radio equipment that is marketed or sold within the EU to comply and to have the mark, it explicitly excludes from the requirements any equipment constructed by licensed amateurs, and self-assembly radio kits, and any equipment modified by or sold only to licensed amateurs.

Bear in mind that if you decide to build or obtain any equipment without the CE mark you are assuming the responsibility for its safety and for the compliance with the radio regulations set out by ComReg, which include EMC and strict rules on the limits of any spurious radio emissions.

All reputable manufacturers of amateur radio equipment test it for compliance with the EU regulations. They provide the CE mark and further details regarding the tests. You may need to find the compliance documents on the manufacturers' web sites, but the CE mark must be present on the case of the device. While it is still your responsibility to use such equipment safely, you can at least rely on their certification to know that the device complies with the radio regulations, especially those related to EMC.

If in doubt, do not use equipment that has no CE mark or test certificates.

23 Phonetic Alphabet

ONE EXAM QUESTION · SECTION B1

Both the ITU and ComReg regulations require that all radio transmissions are identified with a call sign. Furthermore, ITU regulations also require that the PHONETIC ALPHABET is used whenever it is necessary to spell out call signs, words, and abbreviations.[411] This is commonly necessary when transmitting using voice in phone operation.

23.1 International Radiotelephony Spelling Alphabet

The phonetic alphabet, also known as the INTERNATIONAL RADIOTELEPHONY SPELLING ALPHABET, the North Atlantic Treaty Organization (NATO) phonetic alphabet, or the International Civil Aviation Organization (ICAO) phonetic alphabet, is commonly used by radio amateurs. It is shown in the two tables on the following pages. The first shows the letters, while the numbers are in the second table.

There also exists the ITU Phonetic Alphabet and Figure Code. Its spelling of the letters is identical to the table shown below. However, the ITU variant has a different way of pronouncing the numbers which radio amateurs do not use.[412] Radio amateurs use the International Radiotelephony Spelling Alphabet shown below.

While Q-Codes and Abbreviations (Chapter 26) have more relevance for Morse communications, the phonetic alphabet is used mainly in phone, i.e., voice, communications as a means of ensuring that key information such as call signs can be understood even when signals are weak or distorted, or when those involved in the communication speak different languages. This is particularly important when dealing with emergency situations and it is also helpful in radio contests.

When speaking, make sure to put the emphasis (stress, accent) on the CAPITALISED syllable. Pay attention to the correct, even if unusual to an English speaker, pronunciation of the numbers. Examples:

- Spelled EI5ABC Echo India Five Alpha Bravo Charlie
- Spoken EI5ABC ECK-oh IN-dee-ah FIFE AL-fah BRAH-voh CHAR-lee
- Spelled OM4WZH Oscar Mike Four Whiskey Zulu Hotel
- Spoken OM4WZH OSS-cah MIKE FOW-er Whiskey ZOO-loo ho-TELL
- Spelled EI90IRTS Echo India Nine Zero India Romeo Tango Sierra
- Spoken EI90IRTS ECK-oh IN-dee-ah NIN-er ZE-RO IN-dee-ah ROW-me-oh TANG-go see-AIR-rah

411 See Appendix 14, Rev WRC-07, ITU Radio Regulations 2020.

412 ITU pronunciation of numbers uses unusual words. They are not used by radio amateurs. 0=Nadazero, 1=Unaone, 2=Bissotwo, 3=Terrathree, 4=Kartefour, 5=Pantafive, 6=Soxisix, 7=Setteseven, 8=Oktoeight, 9=Novenine.

Table 23-A: International radiotelephony spelling alphabet: letters

Symbol	**ITU Code word**	**Spoken (ITU)**
A	Alfa	AL-fah
B	Bravo	BRAH-voh
C	Charlie	CHAR-lee or SHAR-lee
D	Delta	DELL-tah
E	Echo	ECK-oh
F	Foxtrot	FOKS-trot
G	Golf	GOLF
H	Hotel	ho-TELL
I	India	IN-dee-ah
J	Juliett	JEW-lee-ETT
K	Kilo	KEY-loh
L	Lima	LEE-mah
M	Mike	MIKE
N	November	no-VEM-ber
O	Oscar	OSS-cah
P	Papa	pah-PAH
Q	Quebec	keh-BECK
R	Romeo	ROW-me-oh
S	Sierra	see-AIR-rah
T	Tango	TANG-go
U	Uniform	YOU-nee-form or OO-nee-form
V	Victor	VIK-tah
W	Whiskey	WISS-key
X	X-ray	ECKS-ray
Y	Yankee	YANG-key
Z	Zulu	ZOO-loo

Table 23-B: International radiotelephony spelling alphabet: numbers

Symbol	**ITU Code word**	**Spoken (ICAO)**
0	Zero	ZE-RO
1	One	WUN
2	Two	TOO
3	Three	TREE
4	Four	FOW-er
5	Five	FIFE
6	Six	SIX
7	Seven	SEV-en
8	Eight	AIT
9	Nine	NIN-er

24 Call Signs

THREE EXAM QUESTIONS · SECTION B4

24.1 Allocation of Call Signs

To receive a call sign and to be able to keep and operate transmitting radio equipment, an amateur must apply to ComReg for Amateur Station Licence, see 22.3 Obtaining an Irish Amateur Station Licence.

A call sign is an ITU-compliant unique identifier assigned by ComReg. It is part of the licence. Call signs are issued for the lifetime of the licensee. The only occasion when a call sign may change is when an amateur is changing from a CEPT Class 2 to a CEPT Class 1 Licence. If a licence is surrendered or cancelled the call sign will be permanently revoked. Call signs that have been revoked will not be reissued.

24.2 Composition of Call Signs

Call signs follow an internationally recognisable format set down by the ITU. A normal amateur radio call sign contains three sections:

1. one or two characters identifying the nationality of the licence; at least one character will be a letter; letter-number, number-letter or letter-letter combination is possible
2. a single digit (number)
3. a group of not more than four characters, the last of which must be a letter.

There are many exceptions to the above rules, often for special event call signs. You need to be able to determine if a call sign is valid based on these normal rules. See below a few examples of CORRECT CALLS SIGNS. The dashes "–" in these examples only highlight the separate call sign sections, they are not part of the call sign.

- EI–6–XYZ
- 2E–3–ØRGD
- M–6–A

Examples of INCORRECT CALL SIGNS:

- 2E–A–BCD — no number in section 2
- EI–4–RGD7 — should not end in a number
- 2–6–A — no letter in section 1

24.3 Irish Call Signs

Normal Irish call signs consist of the country identification letters EI, pronounced *Echo India,* a single digit, and either a one, two, three or a four-letter suffix:[413]

EI3F
EI3RDB
EI6ABCD

Stations operating from Irish offshore islands use prefix EJ, *Echo Juliett,* instead of EI. You do not need to apply to use EJ, just change EI to EJ when on offshore islands:

EJ3F

Distinctive call signs, which may not always comply with the normal rules, may be issued by ComReg for special event stations, such as:

EI90IRTS

24.4 Call Sign Usage

The Irish Wireless Telegraphy Act makes it a legal requirement for you to identify yourself in all amateur radio transmissions in line with the ITU regulations, see also 20.7 Frequency of Identification.

- Amateur stations are required to identify themselves by transmitting their call sign *at short intervals* during their transmissions.
- Call signs must be suffixed with /M, pronounced *slash mobile,* when operating from a land-based vehicle, and with /MM, *slash maritime mobile,* when on a water vessel, see 22.7 and 22.8.[414]
- When operating /M or /MM the call sign and the location of the station must be sent at the beginning and end of a contact with each station, or at intervals of 30 minutes whichever is the more frequent.

No other suffixes are allowed by the Irish regulations. A call sign must not be suffixed /P, /QRP or in any way other than /M or /MM. You can say that you are operating portable, or low power, however, current regulations do not permit you to add such a suffix to your call sign. See also footnote 403 on page 330.

413 Normal in this context means call signs issued to licensed radio amateurs who want a traditional station. Other types are issued for special purposes: beacons, automated stations, repeaters, clubs, and for licensed visitors from non-CEPT countries availing of reciprocal agreements during their short visit to Ireland. Visitor call signs have letter V just after the number, for example, EI9VAB.

414 The *IARU Ethics and Operating Procedures* guide recommends that you pronounce it as *stroke.* That is what you may hear on the air. COMREG guidelines 09/45 specify *slash.*

25 Radio Spectrum Allocation in Ireland and IARU Band Plans

SEVEN EXAM QUESTIONS · SECTION B5 B3

25.1 Spectrum Allocation in Ireland

ComReg publishes a very detailed document, the *Radio Frequency Plan for Ireland,* that describes all radio frequency allocations in the entire radio spectrum and its permitted uses.[415] Large portions of the spectrum have been allocated to amateur radio in Ireland. You are not required to study that document, but you should be aware of its existence and its purpose.

The ComReg document 09/45 *Amateur Station Licence Guidelines* details which frequencies are allocated to amateur use in Ireland. This document also restricts the power levels allowed on those frequencies. It also specifies the types of signals, identified by their ITU emission designators, that are permitted for use on some of those frequencies which are unique to Ireland.

! You must comply with ComReg frequency allocation as a condition of your licence. It is illegal to transmit on any frequencies outside of the licenced allocation, with the exception of a small range of frequencies that are exempt from licensing, such as the Citizens Band (CB) which are subject to separate regulations.[416]

- For those bands that are in wide, international amateur use, ComReg does not specify the permitted types of signals and their recommended frequencies or bandwidths. Instead, ComReg encourages all amateurs to follow the IARU R1 Band Plan, and any other national band plans, regarding specific frequencies, types of signals and modes of operation. See also 20.6 Emission Designators.
- By encouraging compliance with the IARU and national band plans ComReg recognises the principle of SELF-REGULATION in amateur radio to ensure equitable usage of the frequency bands by all licensees and to mitigate any potential interference.

The ComReg guidelines have priority over the IARU R1 Band Plan. If the two documents are in conflict, the ComReg document always takes precedence. You need to know how to use the ComReg document, and the differences between it and the IARU Band Plan. However, you do not need to memorise all the frequencies. You only need to learn and remember some of the frequencies listed in this chapter.

415 www.comreg.ie/industry/radio-spectrum/radio-frequency-plan-for-ireland

416 Current list of COMREG licence exemptions is at www.comreg.ie/industry/radio-spectrum/licence-exemptions/list-of-licence-exemptions.

25.2 Band Plans

The three IARU regions adopt voluntary band plans for the frequency bands allocated to the amateur service by the ITU. For the exam, we are concerned only with the IARU R1 band plans. However, being aware of the band plans in the other regions that you wish to contact will improve your chances.

Band plans allocate specific segments to particular modulation types and based on bandwidth. Modes and their bandwidths are explained in Chapter 11 Modulation and Modes. Band plans are defined in considerable detail to provide for a wide range of requirements. You must learn how to use the band plans. You should refer to them every time before you transmit.[417]

Table 25-A shows the full IARU R1 band plan for the 80 m band. You must know the meaning of everything shown in a band plan. You must learn how to use it, but you do not need to memorise everything. This and the following sections will explain what you must learn and memorise.

Table 25-A: IARU R1 detailed 80 m band plan (effective 01 June 2016)

	FREQUENCY SEGMENT (kHz)	MAX BANDWIDTH (Hz)	PREFERRED MODE AND USAGE		
3,5 MHz	3500 - 3510	200	CW	Priority for inter-continental operation	
	3510 - 3560	200	CW	CW contest preferred	3555 kHz - CW QRS Centre of Activity
	3560 - 3570	200	CW		3560 kHz - CW QRP Centre of Activity
	3570 - 3580	200	Narrow band modes	Digimodes	
	3580 - 3590	500	Narrow band modes	Digimodes	
	3590 - 3600	500	Narrow band modes	Digimodes, automatically controlled data stations (unattended)	
	3600 - 3620	2700	All modes (1)	Digimodes, automatically controlled data stations (unattended)	
	3600 - 3650	2700	All modes (1)	SSB contest preferred	3630kHz – Digital Voice Centre of Activity
	3650 - 3700	2700	All modes	3690 kHz – SSB QRP Centre of Activity	
	3700 - 3775	2700	All modes	SSB contest preferred	3735 kHz – Image Centre of Activity 3760 kHz – R1 Emergency Centre of Activity
	3775 - 3800	2700	All modes	SSB contest preferred – Priority for inter-continental operation	

The lines in the IARU band plans are coloured according to the bandwidth. The columns in the above band plan have the following meanings, which you must know.

1 Band — 3,5 MHz refers to the entire 80 m band, which is also known as the 3.5 MHz band. This column uses the continental European number convention that uses a comma for a decimal point. The intended meaning is 3.5 MHz, or 3500 kHz.
2 Frequency Segment (kHz) — 3500–3510 means the range from 3 500 kHz to 3 510 kHz, which is equivalent to 3.5 MHz–3.51 MHz.[418]

417 Download IARU R1 band plan from the band plans section of irts.ie/downloads.
418 1 MHz = 1 000 kHz, 1 kHz = 0.001 MHz. And so: 3 510 kHz = 3.51 MHz, 3.8 MHz = 3 800 kHz. See section 3.2.2 Metric Prefixes on page 14.

3 MAX BANDWIDTH (Hz) — The maximum bandwidth that can be used by a single transmission. Bandwidths of different modes are explained in Chapter 11 Modulation and Modes.
4 PREFERRED MODE AND USAGE — This column shows the allocated modes on the left-hand side. The additional information on the right denotes the preferred usage of the given frequency range. CENTRE OF ACTIVITY refers to a frequency on which, or near which, the preferred usage should take place.

For example, the preferred range for intercontinental voice communication using LSB would be in the 3775–3800 kHz range on the 80 m band.[419] Slow speed CW (QRS) should be used in the vicinity of 3555 kHz. Q-codes are explained in Chapter 26.

You should remember that the low frequency end of each of the bands is typically reserved for CW, and the wide band modes such as SSB or FM are at the high frequency end, with data modes somewhere between the two.

Observe that CW may be used across all frequency ranges, except for the frequencies where you are not supposed to transmit at all, unless authorised, such as propagation beacon frequencies, or the emergency centres of activity when they are in emergency use.

Band plans are widely accepted by amateurs, and adherence to them minimises interference between modes. It promotes equitable use of the radio spectrum, whilst preventing accidental conflicts. On the other hand, you may also find that conflicts do occasionally arise regarding some frequencies whose use may be routine for some amateurs, but obscure to others because it is not mentioned in the band plans. To resolve such conflicts, the IARU constantly works on updating the band plans to follow the usage patterns and the needs of all radio amateurs. Although the process takes a couple of years or so, band plans change from time to time.

Both COMREG and IARU documents are subject to change. All amateurs should be aware of when such changes occur. Consider subscribing to COMREG e-alert notifications about radio spectrum publications.[420] You should also regularly monitor news and announcements by the IRTS which detail important upcoming changes.

25.3 OPERATIONAL BANDS

Amateurs in Ireland have access to *many* more bands than the popular ones, which are discussed in this chapter, and shown in Table 25-C on page 343. The data shown here has been simplified for exam purposes. You should learn to use, and you should always refer to the detailed IARU R1 band plan before you transmit. There are several things that you must learn for the exam.

419 As discussed later, LSB is the preferred SSB mode on 80 m.
420 Visit www.comreg.ie/publications, click *Get email alerts*, and select Publication Categories of interest, such as Radio, Radio Frequency Plan for Ireland, and Spectrum.

- No SSB communication is allowed on the 30 m band, which only permits narrow-band modes, including CW and some data,[421]
- for SSB voice below 10 MHz, except on the 60 m band, you should use LSB, while above 10 MHz and on the 60 m band you should use the upper sideband USB.[422]

Although you do not need to memorise any detailed band plans, other than the simplified 80 m band plan from Table 25-B on page 342, you must memorise the following information for the 160, 80, 60, 40, 30, 20, 17, 15, 12, 10, 4, 2 m, and 70 cm bands:

- the band's edges, that is, the lowest and the highest frequencies of the band on which you are allowed to transmit
- power limits
- status of allocation: primary or secondary
- if contests are permitted
- if maritime mobile use is permitted
- if there are frequencies allocated to Emergency Centres of Activity.

This information is in Table 25-C on page 343. You also need to memorise the frequencies that you must be careful about. They are in Table 25-D and Table 25-E:

- propagation beacons
- the most important Emergency Centres of Activity.

25.3.1 80 m Band Plan

You must memorise the simplified version of the 80 m band plan shown in Table 25-B. All frequencies are in kHz.

When a band plan preferred mode and usage specifies ALL MODES, indeed, that means all of them, including CW, digital modes, and voice modes. The important practical consequence is that CW is permitted on all the frequencies on which you are allowed to transmit. It would be a mistake to assume that CW use is only limited to the lower portion of the band plans. Similarly, digital modes can be used not only in the central section of the band plans, but also in the higher sections. However, digital modes cannot be used in the lowest portion that is reserved for CW. This principle applies to the other bands too because other band plans are similar to the 80 m one.

421 Although IARU R1 band plan does not permit voice communication on the 30 m band, some African countries south of the equator (part of Region 1) and Australia (Region 3) do allow SSB on a portion of the 30 m band, between 10.120–10.130 MHz at present, with plans to reduce it to 10.125–10.130 MHz in the future. You may hear their voice on the 30 m band when propagation is strong.

422 Applies to voice SSB and not to digital or CW transmissions. Some modes, such as RTTY, always use LSB. USB is more popular with other digital modes like FT8. CW uses neither USB nor LSB because it only interrupts the AM carrier.

Table 25-B: IARU R1 simplified 80 m band plan

Frequency Segment kHz	Preferred Mode and Usage
3500–3510	CW, priority for intercontinental operation
3510–3560	CW, contest preferred
3560–3570	CW
3570–3600	Narrow band modes[423] / digimodes
3600–3650	All modes, SSB contest preferred Lowest dial setting for LSB voice on 80 m is 3603
3650–3700	All modes
3700–3775	All modes, SSB contest preferred
3775–3800	All modes, SSB contest preferred Priority for intercontinental operation

25.3.2 Irish Regulations Regarding 60 m Band

In addition to the 60 m IARU R1 frequencies that permit 15 W EIRP, you can also use a set of SPOT FREQUENCIES, listed in Annex 1 of the COMREG guidelines 09/45, using up to 200 W PEP. You do not need to know them for the exam.[424]

25.3.3 Band Edges, Status, Power, Restrictions, Emergency Use

You need to remember this entire table.[425] Columns have the following meaning:

1. BAND: ITU band designation and the wavelength, in metres or centimetres, that is used to refer to the band's frequency range. Make sure to also learn all the ITU band names in Table 7-A on page 82.
2. FREQUENCY MHz: the lowest and the highest frequency allocated to amateur use in the given band. It is illegal to transmit outside of those ranges.
3. STATUS: status of allocation to amateur radio use, see 20.5.
4. POWER LIMIT: maximum permitted output power, in W and in dBW.[426] Make sure to also learn the power limit exceptions:

423 This frequency range is further subdivided depending on the bandwidth of the mode. You need to understand that concept, but you are not required to memorise the breakdown for the exam.

424 There are six spot frequencies at the time of writing. Although up to 200 W PEP is allowed when using them, this higher level of power does not apply to the range of frequencies listed in the IARU band plan. The higher power level only applies to the six spot frequencies outside the IARU band plan.

425 Colour shading in Table 25-C is only a memory aid. The darker green 30 m, 17 m, and 12 m bands are known as the WARC bands. They were allocated to amateur use by the World Administrative Radio Conference (WARC) in 1979. Due to their small bandwidth relative to the other bands, the IARU R1 band plan states that *contest activity shall not take place* on those bands, like also on the 60 m band.

426 See also sections 9.3 Absolute Power in and 15.20 Effective Power: EIRP and ERP.

4.1 PEP limits are measured at the output of the transmitter or an amplifier, for all the bands except 60 m.
4.2 15 W EIRP applies only to the contiguous 60 m range: 5.3515–5.3665 MHz.
4.3 200 W PEP applies to each of the six 60 m spot frequencies, see 25.3.2.
4.4 10 W PEP when operating /MM (maritime mobile) if band is allowed, see 22.8.
4.5 50 W PEP limit when operating /M (land mobile), see 22.7, with more exceptions:
4.6 25 W PEP is the land mobile limit on 4 m.
4.7 10 W on 160 m above 1.850 MHz also applies to land mobile.
4.8 15 W EIRP in the contiguous part of 60 m band also applies to land mobile.

5 CONTESTS: is contest activity allowed?
6 /MM: is maritime mobile operation allowed?
7 EMERGENCY: does this band contain any frequencies designated as emergency centres of activity? See 25.3.5 and 27.3.

Table 25-C: Operational bands: edges, status, power, restrictions

Band		Frequency MHz	Status	Power Limit PEP except 60 m EIRP (not /M or /MM)	Contests	/MM	Emergency MHz
MF	160 m	1.810–1.850	Primary	400 W (26 dBW)	Yes	No	
		1.850–2.000	Primary	10 W (10 dBW)	Yes	No	
HF	80 m	3.500–3.800	Primary	400 W (26 dBW)	Yes	Yes	3.660
	60 m	5.3515–5.3665	Secondary	15 W EIRP (12 dBW)	No	No	
	40 m	7.000–7.200	Primary	400 W (26 dBW)	Yes	Yes	7.115
	30 m	10.100–10.150	Secondary	400 W (26 dBW)	No	No	
	20 m	14.000–14.350	Primary	400 W (26 dBW)	Yes	Yes	14.300
	17 m	18.068–18.168	Primary	400 W (26 dBW)	No	Yes	Yes
	15 m	21.000–21.450	Primary	400 W (26 dBW)	Yes	Yes	Yes
	12 m	24.890–24.990	Primary	400 W (26 dBW)	No	Yes	
	10 m	28.000–29.700	Primary	400 W (26 dBW)	Yes	Yes	
VHF	6 m	50.000–52.000	Secondary	100 W (20 dBW)	Yes	No	
	4 m	69.900–70.500	Secondary	50 W (17 dBW)	Yes	No	Yes
	2 m	144.000–146.000	Primary	400 W (26 dBW)	Yes	Yes	Yes
UHF	70 cm	430.000–432.000	Primary	50 W (17 dBW)	Yes	No	Yes
		432.000–440.000	Primary	400 W (26 dBW)	Yes	No	Yes

25.3.4 Propagation Beacons Frequencies

Unless you have a special authorisation from ComReg to operate an automatic beacon and you are a member of a recognised beacon group, such as the International Beacon Project, the IARU R1 band plan does not permit you to transmit on the beacon frequencies. These BEACONS are used by radio amateurs to determine propagation conditions. You must memorise only the following beacon frequencies for the most popular bands:

Table 25-D: Beacon exclusive frequencies

MHz
14.099–14.101
18.109–18.111
21.149–21.151
24.929–24.931
28.190–28.225
144.400–144.490 [427]

25.3.5 Emergency Centres of Activity Frequencies

These frequencies have been adopted into the band plans of each IARU region to be a focus for emergency communications in their areas. They were further adjusted by each country to suit their needs. They are not absolute frequencies but instead they are CENTRES OF ACTIVITY and EMERGENCY COMMUNICATIONS may be found ±20 kHz from these centres.

These frequencies are not reserved, and you can use them for other purposes. However, you need to very carefully listen before you transmit to ensure they are not in use. You should be aware of any well publicised emergencies that may be in progress. In those cases, these frequencies must not be used for any other purposes. If in doubt, avoid using these frequencies unless operating in an emergency or when authorised by ComReg, and their public service voluntary radio emergency networks, for example AREN, see Chapter 27 International Distress Signs, Emergency and Natural Disaster Communications.

For the exam, you need to know which bands have emergency centres of activity. Below are the frequencies used in Ireland – some of them are different from the IARU R1 and other countries. You need to memorise the first three shown below, the 80, 40, and 20 m ones, as they are the most important.

427 144.400–144.490 is the *Beacons Exclusive* range reserved in the IARU R1 VHF Band Plan 2020. There are additional frequencies allocated for other beacons in the 144.491–144.493 range, however, you do not need to memorise those for the exam.

Table 25-E: Emergency centres of activity used in Ireland

MHz	
3.660	Irish (different from IARU R1)
7.115	Irish (different from IARU R1)
14.300	IARU R1
18.160	IARU R1
21.360	IARU R1
70.325	Packet Radio (AX.25) and Winlink
70.350	Simplex FM Voice
144.525	Simplex FM Voice (H–H + 10 min)
144.800	AX.25 APRS Communication
144.850	Packet Radio (AX.25) Access Only
430.400	Packet Radio (AX.25)
433.775	Simplex FM Voice

26 Q-Codes and Abbreviations

THREE EXAM QUESTIONS · SECTION B2

26.1 Q-Codes

Q-Codes are standard three-letter codes, that begin with letter Q. They were originally developed to facilitate commercial Morse Code transmissions to speed up the sending of messages and to act as a form of an international language for messages.[428] Q-Codes continue to be used extensively in amateur CW and RTTY transmissions and are also commonly used in amateur voice transmissions, assisting conversations between operators speaking different languages.

Table 26-A: Q-Codes

Q-Code	As a question	As a statement or an answer
QRG	What is the (exact) frequency?	The frequency is ...
QRK	What is the readability of my signals?	The readability of your signals is 1–5[429]
QRL	Are you busy? Is the frequency busy?	I am busy The frequency is in use
QRM	Are you being interfered with?	I am being interfered with[430]
QRN	Are you bothered by atmospherics (static, or other noise of a natural origin)?	I am bothered by atmospherics[430]
QRO	Should I increase power?	Increase your power
QRP	Should I decrease my power?	Decrease your power
QRS	Should I decrease my sending speed?	Decrease your sending speed[431]
QRT	Should I stop my transmission?	Stop your transmission
QRU	Do you have anything for me?[432]	I have nothing for you

428 Q-Codes date from 1909. The first twelve codes were standardised in the 1912 International Radiotelegraph Convention Regulations. We still use some of them, including QRK, QRL, QRM, and QRN.

429 The classic response to QRK? as recommended by ITU uses five numbers: 1=Bad, 2=Poor, 3=Fair, 4=Good, 5=Excellent. These are different from the R (RST) code shown in Table 29-A, even if the intuitive meaning is similar. *For the purposes of the exam,* you are only required to know the R (RST) responses and the overall purpose of the QRK code.

430 Optionally, you can specify how bad it is using a numeric scale from 1–5. 1: Not at all, 2: Slightly, 3: Moderately, 4: Strongly, 5: Very strongly.

431 To indicate your desired speed, e.g. 10 WPM (words per minute), transmit QRS 10.

432 This code is sometimes used in CW as a polite way of implying that if the other operator has nothing further to discuss, then communications should end sooner than later.

Q-Code	As a question	As a statement or an answer
QRV	Are you ready?	I am ready
QRX	When will you call me back?	I will call you back at ... Also: wait, standby[433]
QRZ	Who is/was calling me?[434]	You are called by ...
QSB	Is my signal fading?	Your signal is fading
QSL	Can you confirm reception?	I confirm reception
QSO[435]	Can you make contact with ...? Can you communicate with ... directly?	I can communicate with ... (directly)
QSX	Can you listen on ...?	Listen on ...
QSY	Shall I start transmitting on ...?	Start transmitting on ... frequency? Also: change frequency to ...[436]
QTH[437]	What is your location?	My location is ...
QUF	Have you received the distress signal sent by ... (name and/or call sign)? See Chapter 27 International Distress Signs, Emergency and Natural Disaster Communications	I have received the distress signal sent by ... (name and/or call sign) at ... hours. Stop transmitting, listen, and follow instructions if any are given to you. This in an EMERGENCY SIGNAL. Pass on the message to emergency services (telephone 999 or 112) unless you are trained to deal with emergencies.

Q-Codes have been developed over a very long period of time. Some of the codes have evolved and slightly changed their meaning over the years. You are supposed to

433 If a short number follows, such as QRX 3, it is usually taken to mean *Wait for three minutes.* Otherwise, you can specify a time for the subsequent call. QRX on its own is often used to say *please wait,* for example if you have to attend to something else but you wish to resume the contact shortly.

434 You will hear this code very often. If you have not understood the call sign of the calling station, you could ask QRZ? for a repeat. Or, if several stations replied to your call, you could ask QRZ? after you have finished a brief contact with one of the calling stations. In Morse, you will also hear a question mark ? on its own in the role of QRZ? as it is even shorter to send.

435 In addition to being a Q-Code, QSO is also a common abbreviation for a *radio contact.* You could say *Thank you for this nice QSO!* meaning *Thank you for this nice radio contact!*

436 You can specify a frequency in any way that would be clear to the other operator. For example, if the frequency is becoming unusable, you may want to transmit QSY 7055 meaning *Change frequency to 7055 kHz* or something simpler like QSY UP 1 meaning *Change to a frequency 1 kHz higher.*

437 Just like QSO, QTH is often used not only as a Q-Code, but also as a generic abbreviation meaning *location.* For example, you could say *QTH Wicklow* to mean *My location is Wicklow.*

learn the current, modern meaning listed in Table 26-A. Some historical meanings have been listed in the footnotes.

Readability, Strength, and Tone (RST) codes are discussed in section 29.5.

26.2 Q-Code as a Question or an Answer

It is important to understand how to use a Q-Code to ask a question and how to use it to provide an answer. In telegraphy, simply add a question mark "?" after the code to make it into a question. In telephony, if it is appropriate to use a Q-Code, simply speak with a questioning tone of voice.

For example, in telegraphy, to ask: *Is this frequency busy?* you could transmit using CW or RTTY:

- QRL?

To which you may receive a response such as:

- QRL

Which, in turn, would mean: *Yes, the frequency is in use*. You could also get a different reply, such as *Yes, Y,* or *C* (confirm). Essentially, QRL without a question mark indicates a statement or an answer, while with the question mark, it becomes a question.

On phone, if you are making a quick contact, you may want to receive a verbal acknowledgement of some information that you have just exchanged. Using a questioning tone of voice to ask *QSL?* is a common way to do that. It means *Can you confirm reception of the information we have just exchanged?* In reply, the other operator may just say *QSL* to acknowledge that they have received and understood the exchange.

Q-Codes are a human language, and they can be used for other, similar purposes depending on the context. For example, you could also use the QSL code to say *QSL via buro* which would have the meaning of *I will confirm (acknowledge) our contact by sending a card via the bureau.*

26.3 Operational Abbreviations

Like Q-Codes, operational abbreviations are used in discussions and radio communications to speed up the sending of messages and to facilitate conversations between operators speaking different languages. The relevant ones that you need to know are listed in Table 26-B.

Some of the operational abbreviations, especially when used in a conversation, are the same as a Q-Code from which they originate. For example, two radio amateurs may be conversing about a place, referring to it as *a QTH,* saying something like *Have you seen the new QTH where the awards dinner is going to be?* Clearly, they are not using QTH as a strict Q-Code to ask or confirm their location. That abbreviation now

simply means *a location*. Or, you may hear someone say *Nothing seemed to happen on that QRG.*

Table 26-B: Operational abbreviations

Abbreviation	Meaning
Being QRV	Being ready, being available
BK	Signal used to interrupt a transmission in progress
CQ	General call to all stations, intended to be answered by anyone
CW	Continuous Wave, synonymous with Morse Code
DE	From — used to separate the call sign of the station called from that of the calling station
DX	Long distance, usually meaning on another continent
Going QRT	Leaving the station, stopping transmissions
K	Over — an invitation for the other operator to transmit
MSG	Message
OP	Operator
PSE	Please
RST	Readability, signal-strength, tone-report, see section 29.5
R [438]	Received, also meaning a general *yes* or *confirmed*
RX	Receiver
QRG	Frequency
QRX	Just a moment, please stand by
QSL	I confirm
QSL Card	Paper card that confirms a contact
QSO	Radio contact
QTH	Location
QSY	Change of frequency
SKED	Scheduled call, planned and agreed ahead
TX	Transmitter
UR	Your

438 Even though the correct phonetic spelling of R is *Romeo,* when you hear R used on its own, as a confirmatory operational abbreviation, you will usually hear it spoken as *Roger* or even *Roger Roger.* This is common. Even if you say *Roger* to confirm something, you should still pronounce R as *Romeo* in other cases when spelling call signs or anything else that requires the use of the phonetic alphabet shown in Table 23-A: International radiotelephony spelling alphabet: letters on page 335.

27 International Distress Signs, Emergency and Natural Disaster Communications

THREE EXAM QUESTIONS · SECTION B3

27.1 Distress Signals

A DISTRESS SIGNAL is an internationally recognised way of calling for help. These signals must only be used where there is grave and imminent danger to life. There are two distress signals, one used in telegraphy and one for telephony.

27.1.1 Radiotelegraphy (Morse) Distress Signal

The distress signal used in telegraphy is SOS. In CW it is sent as the following Morse code sequence, without the usual spaces between the characters:

• • • – – – • • •
(dit-dit-dit-dah-dah-dah-dit-dit-dit)

27.1.2 Radiotelephony (Voice) Distress Signal

The distress signal to use when speaking on the phone is:

MAYDAY

27.2 Emergency and Natural Disaster Communications

ITU regulations permit the use of amateur radio stations for transmitting international communications on behalf of third parties only in case of emergencies or disaster relief. National administrations determine the applicability of this provision to amateur stations in their jurisdictions. ITU encourages national administrations to take the necessary steps to allow amateur stations to prepare for and meet communications needs in support of disaster relief.

ComReg has followed this ITU guideline. In Ireland, the Amateur Radio Emergency Network (AREN) is an example of a public service voluntary radio emergency network that is approved by ComReg for this purpose.[439]

If you are interested in supporting emergency communications, please join and receive further training from an approved emergency network organisation, such as AREN. Only a properly trained operator can be relied on provide efficient and effective emergency communications. However, if you own, manage, or operate equipment, such as repeaters or gateways, which can be of use in an emergency, you

439 To learn about AREN and for further training, please visit www.aren.ie.

can offer them without having to participate in passing emergency communications traffic. Contact AREN or another emergency network organisation to make your equipment available.

27.3 Emergency Frequencies

Band plans make provision for EMERGENCY CENTRES OF ACTIVITY where you are likely to hear emergency traffic during times of need.

These amateur frequencies are not reserved, and you can use them for other purposes. However, you need to very carefully listen before you transmit to ensure they are not in use. You should be aware of any well publicised emergencies that may be in progress. In those cases, these frequencies must not be used for any other purposes. If in doubt, avoid using these frequencies unless operating in an emergency or when authorised by ComReg and their public service voluntary radio emergency organisations like AREN.

Make sure to learn which amateur bands have these centres of activity from Table 25-C on page 343. All emergency frequency centres of activity are listed in Table 25-E on page 345.

27.4 Role of Licensed Radio Amateurs in Emergency Communication

The remainder of this section explains the essentials of emergency communications that you must be aware of. Please note, that without further training in this area, for example as provided by AREN, you should not assume any emergency communication roles beyond what is outlined in this section. You must not impede emergency operations through a lack of knowledge of emergency operating procedures, no matter how much you wish to assist.

This section is based on the *IARU R1 Emergency Operating Procedures,* adapted by AREN for Irish needs.[440]

If you own, operate, or manage equipment and communication modes, such as repeaters, gateways, JS8CALL, APRS facilities, Winlink, AREDN etc., please consider making those available to an approved emergency communications organisation, such as AREN, even if you do not plan to undertake further emergency traffic training. Your contribution could be valuable even if your role was limited to knowing when to switch on the equipment and software, for instance, your Winlink facility, and to keep an eye on to ensure that it is working correctly for the trained people to use. Contact AREN or another approved organisation for more information.

440 www.iaru-r1.org/about-us/committees-and-working-groups/emcomm

27.4.1 Communications Emergency

A COMMUNICATION EMERGENCY exists when a critical communication system failure puts the public at risk. Emergency telecommunications may also be referred to as emergency communications or EMCOMM.

27.4.2 Served Agencies

A SERVED AGENCY is any organisation which may request emergency communication assistance from you.

PRINCIPAL EMERGENCY SERVICES (PES) are the blue light services that respond to normal emergencies in Ireland, that is: *An Garda Síochána,* the *Ambulance Service* and the *Fire Service.* A fourth principal emergency service, the *Irish Coast Guard,* is responsible for the initiation, control, and co-ordination of maritime emergencies in the Irish territorial waters, harbours, and coastline. The principal emergency services are normally the first services to respond to major emergencies.

PRINCIPAL RESPONSE AGENCIES (PRA) are the agencies designated by the government to respond to major emergencies, that is, *An Garda Síochána,* the *Health Services Executive* and the *Local Authorities.* Each principal emergency service is part of a larger principal response agency, for example: the Fire Service is a Local Authority service. Due to the nature and complexity of major emergencies, the staff and resources of the wider agency are required, both to manage the consequences and the aftermath of the major emergency event and to co-ordinate their response with the other agencies.

There are also VOLUNTARY EMERGENCY SERVICES (VES) that may request your assistance and which you should treat as a served agency. Those include Civil Defence, Irish Red Cross, and several other organisations which you should become familiar with if you undertake further emergency communications training.[441]

27.4.3 Net

A NET is short for a COMMUNICATIONS NETWORK. In emergency communications terms, this refers to an emergency radio communication network, or simply an EMERGENCY NETWORK. If you undertake further emergency communications training you will learn about net control stations and procedures, including how they are set up, managed, and how they ensure efficient operations.

441 As of January 2024, those additional Volunteer Emergency Services include: Order of Malta Ambulance Corps, St John's Ambulance Service, Mountain Rescue Teams, Cave Rescue Teams, Search and Rescue Dog Associations, River Rescue Units, Community Inshore Rescue Units, RNLI, Sub-Aqua Units, 4x4 Response.

27.4.4 Who You Are Not

As important as who you are, knowing who you are not, is also vital. There are limits to your responsibilities as an emergency communicator, and it is important to know where to draw the line, especially if you have no further training.

- You are not a first responder. Except in rare cases of chance, you will seldom be the first on the scene.
- You have no authority. In most cases, you cannot make decisions for others, or make demands on the agency you serve or any other agency. The only decisions you can make are whether to participate or not, and those affecting your own health and safety.
- You cannot do it all. When the agency you are helping runs short of doctors, cooks, or traffic officers, it is not your job to fill the void. In most cases, you are not trained for it. That does not mean you cannot lend a hand to fill an urgent need when you are qualified and competent to do so.
- You are not in charge. You are there to temporarily fulfil the needs of an agency whose communication system is unable to completely do its job. They tell you what they need, and you do your best to comply.

It may be helpful to think of emergency telecommunication volunteers like unpaid employees. If you maintain the attitude that you are an employee of the agency you are serving, with all that employee status implies, there is little chance for you to go astray. You are there to help solve their communication problems. Do whatever you can, within reason, to accomplish that goal, and avoid becoming part of the problem.

27.4.5 Day-to-Day vs. Emergency Communication

In your daily amateur radio life, there is no pressure to get any messages through. You do things at your leisure, and no one's life depends upon you. In an emergency all that changes. The list of differences is lengthy but here are some examples.

- Instead of one leisurely net a day, emergency communicators are often dealing with several continuous nets simultaneously to pass critical messages within a limited time frame.
- Unlike public service events where the communicators serve primarily under the direction of one lead organisation, emergency communicators may need to interact with several key organisations within a limited period.
- Unlike typical home installations, emergency stations must be portable and able to be set up and operate anywhere in a very short time.
- Unlike contesting, which involves contacting many random stations for points, emergency communicators need to contact specific stations quickly to pass important messages. Teamwork is important, not competition between stations.

27.4.6 Means of Emergency Communication

When you become a skilled radio operator, perhaps even proud of the equipment in your station, it is vital to remember that your primary task is communication. If a served agency asks you to deliver a shelter supply list to their headquarters, you should be prepared to use any means required, not necessarily radio. Your job is to get the message through by whatever means possible. You should use your ingenuity to accomplish the task. Do not think about how to use radio to send the message, just think about the best and fastest way to send it. If some method would work well, choose it. If that means using amateur radio, so much the better. If an agency asks you to use their radio system, do it. Your operating and technical skills are just as important as your radio resources.

27.5 Measures in Case of Emergency

Regardless of your level of training you need be familiar with and follow these measures.

- If you hear any of the following words *emergency, welfare traffic,* MAYDAY, SOS, QUF, stop transmitting and listen.[442]
- If you receive such traffic, listen carefully, and write down all you can hear.
- Do not leave the frequency before you are sure that you cannot help or that somebody else is helping.
- Do not transmit before you are sure that you can help.
- If a net control station is giving you instructions, follow those instructions.
- ! Call 999 or 112 to pass any messages that you have heard if you are unsure what else to do with them.

442 As explained in section 27.1 Distress Signals, to send a distress signal using phone (voice) you should speak the internationally-recognised distress word MAYDAY and not the word SOS. The SOS signal should only be sent by you as a distress signal using radiotelegraphy, for example using CW. That is the correct practice, and you must know it for the exam. However, others may not be aware of the correct procedure. The person you may be hearing may not be trained and may be under some significant stress. You should always apply common sense and if you hear someone call SOS or some other words that indicate that they are in distress and that they are asking for help.

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28 Social Responsibility of Radio Amateur Operation and the Code of Conduct

THREE EXAM QUESTIONS · SECTION B6

You should read the *IARU Ethics and Operating Procedures for the Radio Amateur* Edition 3 (or later) guide while studying.[443] Portions of that guide have been reproduced, rephrased, or summarised in this section. These portions are part of the exam syllabus. The copyright of the original authors © John Devoldere ON4UN and Mark Demeuleneere ON4WW is hereby acknowledged in line with the copyright permission outlined on page 2 of that IARU guide.

Please note that this document is currently being revised by the IARU R1. The overall tone and the language of the original document is being modernised. In anticipation of the upcoming edition, the author of this chapter has rephrased and summarised the IARU guidance using a more modern language and tone, whilst adhering closely to the meaning and the intent presented in the 3rd edition of the IARU guide. Once it has been published, this Study Guide will be updated, first online, and later in print.[444]

28.1 Basic Principles

There are basic principles that govern the CODE OF CONDUCT on the amateur radio bands.

- Social feeling and a friendly spirit. Large numbers of radio amateurs are all enjoying radio on the same airwaves, which is a space we all choose to share. We are never alone in that space. Radio amateurs aim to be colleagues and friends, and act accordingly, in consideration and with respect to the feelings of other radio amateurs.
- Tolerance. Not all other radio amateurs necessarily share each other's opinions, and they may not consider your opinions to be the best ones for them. It is helpful to remain tolerant and understanding of people and their differing opinions.
- Politeness. Always be polite, courteous, and gentle. Avoid using rude language or abusive words when on the air. Everyone can listen, and there may be a lot of people listening to what you say, even if they are not in a conversation with you. Remain in control of your language and tone.
- Comprehension. Others may not have the same understanding of a subject as you, especially if you happen to be an expert in that area. If you hear something that you know to be wrong, and if you wish to do something about it, act positively. Offer

443 Download from www.irts.ie/downloads.

444 Suggestions for changes to the *IARU Ethics and Operating Procedures for the Radio Amateur* guide should be emailed to iaruguide@irts.ie. Until a new guidance document has been released, the 3rd edition is the IARU guidance referred to in the Irish HAREC exam syllabus, sections B6 and B7.

helpful, constructive criticism if necessary, aiming to politely explain the issue. Avoid causing negative feelings by using strong or impolite language.

28.2 Danger of Conflict

The radio spectrum is a space shared by all radio amateurs. Everyone may have their own interests and competitive goals, and it all must happen on the shared radio bands. A few of the millions of operators are likely to come in conflict with each other from time to time.

For example, you suddenly hear someone making a CQ call, or talking to someone else, on the same frequency that you have been using. How is that possible if you were there for more than half an hour, during which the frequency was clearly only used by you? Indeed, the other station may be thinking the same, that you have just intruded on their frequency.

The propagation conditions change all the time. The chances are that the stations that previously could not hear each other suddenly can. There is no malice, it is just ionospheric conditions that are changing, and perhaps they brought you within range of each other.

28.3 How to Avoid Conflict?

Many conflicts are caused by the lack of awareness of operational guidance. Resolving a conflict is harder than avoiding it in the first place. Many conflicts could be avoided if operators were aware of operational procedures. The *IARU Ethics and Operating Procedures for the Radio Amateur* guide summarises simple operating procedures and guidance that is based on long-term amateur radio practices, some of which were honed by professional radio operators, and some which come from ITU and IARU recommendations.

28.4 The authority vs. Self-discipline in Amateur Radio

In most countries the authorities do not have an in-depth interest in how radio amateurs behave on air, providing that they operate according to the laws and regulations laid down by the authorities. This is also the case in Ireland.

The radio amateur community relies on an element of a SELF-REGULATION and a SELF-DISCIPLINE as the basis of its conduct. An example of self-regulation is the consensual process of iterative development of the IARU band plans. An example of self-discipline is the broad support those band plans receive, permitting equitable usage of the radio spectrum by all amateurs. The Irish communications regulator, ComReg, has recognised these beneficial principles in recommending compliance with the IARU R1 band plans in ComReg document 09/45, instead of making their own suggestions as to what modes of transmission should be used on which segments of the frequencies allocated to amateur radio use.

It does not mean that the amateur radio community has its own police services. Only the authorities can deal with breaches of the law or regulations. Self-discipline,

based on good ethics and compliance with our Code of Conduct has, however, proven to work well for over a century.

On the other hand, if you experience a *deliberate* interference by, or to, other radio spectrum users, you should report it through the correct channels. See section 29.6.1 How to Deal with Spectrum Interference?

28.5 Amateur Radio Language

Another radio amateur may refer to you or themselves as a HAM. It is a colloquial term for radio amateurs.

Radio amateurs address one another using their first name, or nickname, and their call sign. Surnames are used rarely. You may hear someone ask, *have you read any other books by John ON4UN?* This also applies to written communications between radio amateurs.

In writing, part of the amateur radio etiquette is to greet one another using "73". Since 73 stands for *best regards,* it is not necessary to write *best 73* or *73s*.

Radio amateurs say that they *work* each other. To WORK means to make contacts with one another. Contacts are commonly referred to as QSOs.

A longer conversation with another station is known as a RAGCHEW. Some amateurs prefer to ragchew, and others like to make short contacts. Others may like CONTESTING, i.e., participating in live radio contests, aiming to make a large number of error-free and correctly logged contacts. Many amateurs like to do all of those things.

If you used to be a CB operator, you may find that the CB jargon is generally not used in amateur radio. CB terminology may not be understood by radio amateurs because some terms have a different meaning, for example with regards to propagation, station identification, or the use of significantly different radio bands and modes.

Learn the Q-Codes and other operational abbreviations that are widely used during on-air contacts, and even in casual, in-person conversations. See Chapter 26 Q-Codes and Abbreviations. However, you should avoid overusing the Q-Codes, especially in phone (voice). As well as the small number of Q-Codes which are commonly used on phone, there are some other short expressions that stem from CW (Morse Code) and that have become commonplace on phone.[445]

Make sure to only use the phonetic spelling alphabet, see Chapter 23 Phonetic Alphabet. Avoid fantasies which may sound amusing, but which may not help your correspondent understand what you are saying. Do not mix different spelling of words in one and the same sentence. For example: *CQ from ON9UN, Oscar November Nine Uniform November, Ocean Nancy Nine United Nations* would be confusing, especially if band conditions are poor.

The most widely used language in amateur radio is English. If you want to contact stations all over the world it is likely that your contacts will be in English. However,

445 In addition to the popular 73, you may hear OM (man) and YL (woman). There are more, but may not be understood by many operators. See en.wikipedia.org/wiki/Morse_code_abbreviations.

anyone can converse in their language of choice. You may find that non-English speakers sometimes use their national phonetic alphabet with each other.[446]

Because of its reliance on Q-Codes and operational abbreviations, telegraphy contacts, especially in Morse Code, allow those who speak neither English nor the language of their QSO partner to make successful contacts.

28.6 Listen

A good radio amateur starts by listening a lot. You can learn a lot by listening but beware that not all you hear on the bands are good examples. You will witness ineffective operational procedures.

If you are active on the bands, be a good example on the air and apply the guidelines explained in the next section of this guide, and in more detail in the IARU *Ethics and Operating Procedures for the Radio Amateur*.

Above all, ALWAYS LISTEN, before you transmit.

28.7 Use Your Call Sign Correctly

The short word CALL is sometimes used instead of the longer CALL SIGN or *call letters*. Use only your complete call sign to identify yourself. Do not start your transmission by identifying yourself or your correspondent by your or their first name. Do not start by saying: *Hello Mike, this is Louis.*

Identify yourself with your full call sign, not just the suffix. It is against regulations, and illegal in many countries, including Ireland, to identify your radio transmissions by anything other than the exact call sign that was assigned to your station. For example, identify yourself as EI5ABC, and not 5ABC.

If you are operating from a land-based vehicle, or maritime mobile, correctly add the /M or /MM suffix to your call sign, as explained in sections 22.7 and 22.8.

Bear in mind, as discussed in section 24.4 Call Sign Usage, that no other call sign suffixes are permitted for use in Ireland. Other countries may have different rules. For example, operators in the USA may use /QRP as a suffix. It is not permitted under the Irish regulations nor in some other European countries.[447] Of course, you are free to explain in any way you wish that you may be operating QRP (low power). Irish regulations just do not allow you to add the /QRP or the /P suffix, or any suffixes other than /M and /MM, to your call sign.

Always identify yourself frequently, at short intervals, and in line with the regulations. See section 20.7 Frequency of Identification.

Make sure to use the correct prefix if travelling in CEPT countries, see section 21.3.

446 You are likely to hear stations using different phonetic alphabets during international radio contests, even mixing the international version with their national one.

447 In some other countries it is against regulations to add the /QRP suffix, for example, in Belgium.

29 Operating Procedures and Non-Interference

FIVE EXAM QUESTIONS · SECTION B7

You should study the *IARU Ethics and Operating Procedures for the Radio Amateur* Edition 3 (or later) guide prior to the exam. Please read the short note about the upcoming changes to that document, mentioned at the top of page 356.

Some sections of that guide, notably the format of CW CQ calls, have been superseded with updated guidelines published by the IARU in 2014.[448] This chapter shows the operating procedures based on the updated IARU guidelines, which are also in line with the ITU recommendations.

29.1 How to Make a QSO

A QSO is a contact by radio between two or more operators. You can make a general call, known as a CQ, or you can answer someone's CQ, or you call someone who has just finished a contact with another station.

In all kinds of QSOs, including voice, CW, or digital, we do not talk simultaneously. There is always one person speaking, and one or more listening, at a time.

Once the QSO has started, it consists of a series of OVERS. An over can be a short or a longer sentence, or a few sentences, spoken or transmitted by only one operator at a time.[449] An over usually ends with the person saying *over* to indicate to the listening operator that it is their turn to transmit. In Morse, an over is usually ended by sending letters K or KN, which is explained further below.

Which call sign should come first in your transmissions? If you are EI5ABC and W1ZZZ is the person you address, the correct ORDER OF CALL SIGNS is:

- on phone: W1ZZZ from EI5ABC
- or even shorter: W1ZZZ EI5ABC
- or, in Morse: W1ZZZ DE EI5ABC

You always start with the call sign of the person you speak to, followed by your own call.

How often should you identify during a QSO? Irish regulations do not prescribe how often to identify yourself, except when operating mobile or maritime mobile, when you must identify at the start, end, and at least every thirty minutes. Other countries have different regulations. In general, you should identify yourself at the

448 See recommendation VA14_C3_REC_21 from the International Amateur Radio Union Region 1 2014 General Conference, Varna-Albena, Bulgaria, 21–27 September 2014, page 22. www.iaru-r1.org/wp-content/uploads/2019/10/GC_2014_Albena-Conf-Rep.pdf

449 This key principle is also known as *simplex*. Only one transmitting station at a time.

beginning and at the end of each transmission, and frequently enough throughout. Some countries suggest a minimum of at least once every 5 minutes.

A series of short overs is usually considered to be SINGLE TRANSMISSION. In a contest it is not strictly necessary, from the viewpoint of the rule maker, to identify at each QSO. The 5-minute rule has come about as a requirement from the monitoring stations to be able to easily identify stations. From an operational point of view however, the best procedure is to identify at each QSO, but not necessarily each over.

When your correspondent switches the transmission over to you, it is a good habit to wait a brief second before starting your transmission, to check whether someone may be trying to join you or use the frequency.

Short or long transmissions? Preferably make short rather than long transmissions, this makes it much easier for your correspondent if they want to comment on something you said.

29.2 Content of Transmissions

The ITU Radio Regulations, article 25.2, limits the content of transmissions between amateur stations of different countries to communications *incidental to the purposes of the amateur service,* and to *remarks of a personal character.* Those regulations do not limit the contents of conversations between amateurs located in the same country, however, national regulations may impose additional requirements. In Ireland, the key restrictions limit amateur radio to non-pecuniary character, meaning that conducting business on the air is not allowed.

Furthermore, BROADCASTING, including speech or music, requires a different licence than the amateur licence. Amateur radio contacts, except for test signals, CQ or some emergency calls, always have a specific participant, or a group (net) of participants, each identified with their call signs.

- Radio amateurs are not permitted to broadcast to a potentially unknown audience.

29.2.1 Subjects to Avoid

It is a long-standing part of amateur radio etiquette that some subjects should be avoided in radio conversations on the air. The *IARU Ethics and Operating Procedures,* 3rd edition guide states that the following five subjects must be avoided:

1. religion
2. politics
3. business – you can talk about your profession, but you cannot advertise for your business
4. derogatory remarks directed at any group: ethnic, religious, racial, sexual etc.
5. bathroom humour – if you wouldn't tell the joke to a ten-year-old child, don't tell it on the radio.

You should be aware that regulations in countries other than Ireland may further limit the subjects of on-air conversations to only those mentioned in article 25.2 of the ITU regulations. Rather controversially, this is conveyed in the 3rd edition of the IARU guide as a broad prohibition of *"any subject that has no relation whatsoever with the ham radio hobby"*. This part of the IARU guide is under review.[450]

In Ireland, UK, and many other countries, you will hear radio amateurs talk about a variety of subjects that have no connection to amateur radio, including their other hobbies, events, plans, etc. Those may be considered as *remarks of personal character*.

However, to make amateur radio enjoyable for everyone, there is a wide agreement to always avoid the five subjects mentioned on the previous page.

29.3 Making Initial Calls

Remember that when identifying stations in transmissions the call sign of the station being called or worked comes first, and the call sign of the station calling or handing over the transmission comes second.

29.3.1 Selecting a Frequency

If you would like to make a GENERAL CALL, that is, a CQ, or a call to a specific station that you have in mind, but which has not started transmitting yet, you will be the first station to transmit. You have the important responsibility to select an appropriate frequency for the mode and type of your transmission and to ensure non-interference. Follow these steps before you make that first call:

1 Check which portion of the band you should use. Always refer to the IARU R1 *band plan* – keep it handy. Make sure to comply with any additional Irish regulations discussed in Chapter 25 Radio Spectrum Allocation in Ireland and IARU Band Plans.

2 Before calling on a frequency, LISTEN CAREFULLY to make sure it is clear.[451] Avoid selecting frequencies too close to another nearby transmission.[452]

3 If the frequency appears clear, ask:

3.1 On phone: *Is this frequency in use from EI5ABC?* [453]

3.2 In Morse: QRL? DE EI5ABC

450 Suggestions for changes to the *IARU Ethics and Operating Procedures for the Radio Amateur* guide should be emailed to iaruguide@irts.ie. Until a new guidance document has been released, the 3rd edition is the IARU guidance referred to in the Irish HAREC exam syllabus, sections B6 and B7.

451 If you are using a digital mode, such as FT8, use the software spectrum scope to select a frequency (or a frequency offset) that appears clear enough, even if the mode you are using supports simultaneous transmissions by more than one station.

452 If you can just about hear speech-like noise, or speech rhythm from a nearby transmission, consider moving a few Hz up or down. Never select an LSB frequency that is so low, or a USB that is so high, that they would cause you to transmit outside of the band plan allocation. SSB requires 2.7 kHz bandwidth below (LSB) or above (USB) the frequency shown on your transmitter's frequency display.

453 Some operators ask *is this frequency clear?* but that may lead to confusion. A frequency clear to one station may not be to another. It is better to ask *is this frequency in use?*

4 If no one has indicated that the frequency is in use, ask the question once again, listen and wait.[454]
5 If no one is indicating that the frequency is in use go ahead and make the CQ call.

You may be wondering, if you have already listened for a while on an apparently clear frequency, why do you have to ask if the frequency is in use. One station, part of a QSO, may be in a location that you cannot hear. That station could be transmitting on this frequency to someone who is listening. You cannot hear the transmitting station, and they probably will not hear you, because there is no propagation path between you. However, the other station that they are in a QSO with, who is listening, may be in your propagation path. If you were to transmit, they would no longer be able to hear their partner. If you ask if the frequency is in use, their correspondent may hear you and confirm that. If you start transmitting without asking, chances are you will be causing QRM to at least one of the stations on the frequency. Always ask if the frequency is in use, more than once, even if it seemed clear.

If you happen to be in a QSO and you hear someone ask if the frequency is in use, or you hear a QRL?, or just a question mark ? in Morse, you should reply:

- On phone: *Yes*
- Or more fully: *Yes, this frequency is in use*
- In Morse, any of: QRL, R, Y, YES, C

Note how QRL on its own, without a question mark, means *This frequency is busy* in the context above.

29.3.2 Format of a CQ Call

On phone, to make a CQ call inviting any station to reply, speak:

- *CQ CQ CQ from EI5ABC EI5ABC EI5ABC standing by*

In Morse, transmit:[455]

- CQ CQ CQ DE EI5ABC EI5ABC EI5ABC K

454 Although you are supposed to identify all transmissions, you will hear stations only transmit QRL? or even just ? on its own in CW. The reason is not to interfere with a transmission in progress that you may not be hearing. QRL? is less likely to interfere than QRL? DE EI5ABC. You would identify yourself after a QRL? if the frequency was clear when you start your QSO. If you decided not to transmit even if clear, you should identify yourself. For example: QRL? (pause – frequency is clear) DE EI5ABC. Arguably, you could also briefly identify yourself if the frequency was in use, albeit causing some interference. You could transmit: QRL? (pause – frequency is in use) SRI DE EI5ABC. SRI means *sorry*. You must decide between causing some interference or failing to identify your transmission.

455 The structure of Morse calls presented in this guide follows the common practice and is broadly based on the recommendation ITU-R M.1677-1 (2009) in addition to the *IARU Ethics and Operating Procedures Guide,* including the IARU R1 Recommendation VA14_C3_REC_21. See footnote 448.

The final symbol, K, is known as an INVITATION TO TRANSMIT. You will hear different variants of the CQ call on the air, however, this is the one that is recommended by the IARU and ITU.[456]

29.3.3 CQ Calls to Specific Geographic Areas

If you are only interested in hearing from stations on another continent, or stations from specific countries, you can ask for that in your CQ call.

For example, to ask only for stations from Japan to respond, you would call on phone:

- *CQ Japan CQ Japan CQ Japan from EI5ABC EI5ABC EI5ABC standing by*

or, in Morse:

- CQ JA CQ JA CQ JA DE EI5ABC EI5ABC EI5ABC K

Because JA is the national prefix for Japan.[457]

There are many other ways how you could specify who you would like to or would not like to hear from. Consult the *IARU Ethics and Operating Procedures* guide.

29.3.4 CQ DX

If you would like to work only stations located far away from you, which, on HF, means stations on another continent, and on VHF/UHF stations located more than 300 km away, you should make a CQ DX call. On phone, you could call:

- *CQ DX CQ DX CQ DX from EI5ABC EI5ABC EI5ABC standing by*

or to be more specific:

456 You will hear stations which precede the K with a prosign (procedural sign) <AR> meaning *end of message,* and sometimes with the operational abbreviation PSE (please). It is not sufficient to end the CQ call with <AR> alone. If you use the optional prosign, it should be followed by K to invite other stations to transmit. The use of PSE may be courteous, and is optional, but is not recommended in the IARU and ITU guides. An alternative form of a Morse CQ call could be: CQ CQ CQ DE EI5ABC EI5ABC EI5ABC <AR> K. *Prosigns* or *procedural signs,* are used extensively in Morse. They are written as letters between angle brackets <AR> or as letters with a line above them $\overline{\text{AR}}$ to indicate that the letters A and R should be sent without a space between them. Some of the prosigns are part of the COMREG Morse competency exam for Class 1 licences (see 22.3).

457 Japan, like many countries, has many call sign prefixes, including JA, JB, JC, and more. One of them is used to denote the entire country. It is usually the historically first, or the most popular one, of the many prefixes that a country uses. For Japan it is JA. For Ireland it is EI, even though we also use EJ on our offshore islands. There are several sources where you can find those representative prefixes, for example: https://rsgb.org/main/operating/licensing-novs-visitors/international-prefixes/

- *CQ DX CQ DX CQ DX outside Europe this is EI5ABC EI5ABC EI5ABC standing by*

or, in Morse:

- CQ DX CQ DX CQ DX DE EI5ABC EI5ABC EI5ABC K

If a station replies to you who is not DX for you, be obliging and polite. Perhaps they have not heard DX in your call, or maybe you are a new country to them. Make a quick QSO with that station then call DX again, hoping for better results.

When you are selecting frequencies for calling CQ DX you can make use of the sections of the band plan that are recommended for intercontinental operations. By not carrying much local traffic those frequencies may be quieter and more conducive to weaker, long-distance transmissions.

On the receiving side, do not reply to CQ DX unless you are DX to that station.

29.3.5 Format of an Initial Call to a Specific Station

If you would like to call a specific station, for example OM2ABC, and you have already followed the procedure for selecting a clear frequency (see 29.3.1), speak on the phone:

- *OM2ABC OM2ABC OM2ABC from EI5ABC EI5ABC EI5ABC standing by*

or:

- *OM2ABC OM2ABC OM2ABC from EI5ABC EI5ABC EI5ABC calling on sked and listening for you*

A SKED is a scheduled call that, presumably, you have planned to have with OM2ABC. It would be inappropriate to call CQ in this case, as this is not a *general call* to any station, but a call only to OM2ABC.

In Morse, you would transmit:

- OM2ABC OM2ABC OM2ABC DE EI5ABC EI5ABC EI5ABC KN

or:

- OM2ABC OM2ABC OM2ABC SKED DE EI5ABC EI5ABC EI5ABC KN

The KN, or a <KN> at the end indicates that you do not want any other stations to call you, except OM2ABC.[458] If you don't mind other stations interrupting or joining, you can use K on its own.[459]

29.4 Replying to Initial Calls

Replying to initial calls is easy. Remember that the call sign of the station you are contacting always goes first, however, it is not always useful or necessary to transmit it. It is, however, vital that you always identify yourself at this stage of a QSO.

Let's say you are EI6XYZ, and you would like to reply to one of the calls that were placed by EI5ABC, shown in the previous sections.

On phone, you would answer with one of the following replies. You would decide which version to use depending on the context: a casual chat vs. a quick, contest-style QSO. It is generally not necessary to repeat your own call sign many times, because, as you will see shortly, the CQ calling station will repeat back to you what they heard. If you have been misheard, you will have a chance to correct your call sign. If they have not heard you, they will ask you to clarify by repeating whatever they heard, or by asking QRZ? meaning *who called me?* [460]

- *EI5ABC from EI6XYZ over*
- *This is EI6XYZ over*
- *EI6XYZ over*
- *EI6XYZ*

In Morse, you would answer with one of the following:

- EI5ABC DE EI6XYZ KN
- DE EI6XYZ KN
- EI6XYZ KN
- EI6XYZ

Note the correct use of *over* on phone and K or KN in Morse.

458 KN can be written both without the angle brackets, or with them, as a <KN>. This is because KN can be sent as two letters, K and N, with the normal space of one dit between the letters. This is unlike prosigns, such as <AR> which consist of the two letters without any space between them, as if they were a single, long character. Morse code, however, is evolving like any language. Many operators treat KN as a <KN> prosign. A similar situation arises regarding the Morse sequence BK (break in conversation) which is often heard as a very distinct <BK>. See also footnote 456 on page 364.

459 It is rare for stations to join or interrupt a QSO in progress, and many operators use K instead of KN. Instead of interrupting a QSO, it is common to hear a station calling another one that has just ended a QSO. Use of KN should prevent that, however, there are other ways to indicate that you do not wish anyone else to call you at the end of a QSO. Send CL (closing down) or the Q-Code QRT to indicate that you are leaving, in addition to using <SK> that indicates the end of a QSO.

460 You should be familiar with these *operational abbreviations*. See Chapter 26 Q-Codes and Abbreviations on page 346 and note how the questioning tone of voice, or the question mark *?* turn the Q-Code into a question that you want to ask.

At this point the station that called CQ would acknowledge your answer by addressing you by your call sign unless they have not heard you or they started working another station. They may acknowledge you in many different ways, for example, by thanking you for the call, giving you your RST (see below) or sharing other information such as their name or QTH.

For example, on phone, you may hear something along the lines of:

- *EI6XYZ from EI5ABC thank you for your call. Your signal report is... over*

Or in Morse, it might go along the lines of:

- EI6XYZ DE EI5ABC TKS FER UR CALL... KN

The structure of the QSO can continue in many different ways from now on. Much depends on the context and the style of both operators. However, you will always know that they are talking to you because they will use your call sign when they acknowledge you.

Read the *IARU Ethics and Operating Procedures for the Radio Amateur* guide to learn about different ways how to structure the rest of the QSO, how to end it, and how to deal with special situations, such as reception problems, interference, need to change frequencies mid-course, and in contests. The guide also covers operating in different modes: SSB, CW, RTTY, PSK, and SSTV, although it does not discuss the more recent ones, such as FT8.

Learning how to conduct QSOs is a key area where listening, whilst you are studying, can help. Consider joining an amateur radio club to also get some first-hand, friendly advice from experienced operators.

29.5 RST Code

Almost every QSO includes an exchange of SIGNAL REPORTS. Some communication modes, such as FT8, use special reports that include automatically measured signal-to-noise ratios. Phone and CW, on the other hand, use the traditional RST or RS codes.

The RST or RS code is used to report on the quality of a radio signal that is being received. It consists of three (RST) or two (RS) numbers. You need to understand the meaning of all the three values, how to read and interpret the S value, and know what it means when T is anything other than 9. You should also memorise the R code table, but do not memorise S and T tables, because their modern use is a little different than the original meaning.

Table 29-A: R values in RST

R value	Readability
R1	Unreadable
R2	Barely readable, occasional words distinguishable
R3	Readable with considerable difficulty
R4	Readable with practically no difficulty
R5	Perfectly readable

Make sure to understand the meaning and how to communicate S and T in the way that was explained in the text above, including the use of the S-meter. Do not memorise the following two tables.

Table 29-B: S values in RST

S value	Strength
S1	Faint signal, barely perceptible
S2	Very weak
S3	Weak
S4	Fair
S5	Fairly good
S6	Good
S7	Moderately strong
S8	Strong
S9	Very strong signals

Table 29-C: T values in RST

T value	Tone
T1	Extremely rough hissing note
T2	Very rough AC note, no trace of musicality
T3	Rough AC tone, rectified but not filtered
T4	Rough note, some trace of filtering
T5	Filtered rectified AC but strongly ripple-modulated
T6	Filtered tone, definite trace of ripple modulation
T7	Near pure tone, trace of ripple modulation
T8	Near perfect tone, slight trace of modulation
T9	Perfect tone, no trace of ripple or modulation of any kind

- R – READABILITY. This is an assessment of how hard or easy it is to correctly copy (understand) the information being sent during the transmission. It is not uncommon for readability to be less than perfect even if signals are very strong and the other way round. You need to learn the R table.

- S – SIGNAL STRENGTH. It indicates how powerful the received signal is at the receiving location. You should report the number shown on your receiver's S-METER.[461] If the S-meter indicates signal stronger than 9 it is common to report the strength above 9 that is shown in dB on the meter. For example, assuming that R is 5 and the S-meter shows +10 dB above 9, you should use a phrase such as *59+10* or *10 over 59*. This is the most common practice. In rare cases when your receiver has no S-meter, use the table to indicate the signal strength.
- T – TONE. Used only in Morse code and digital transmissions, it describes the quality of the transmitter's modulation. While this part of the RST code is still in use, its relevance has diminished as modern transmitter technology can generally be expected to deliver high tonal quality signals.[462] Since tonal quality is almost always perfect, you would expect to always receive or send a T value of 9. Assuming that you are using good quality modern equipment, rather than historical or DIY, if you receive anything less than T9 that would indicate a problem that needs to be addressed. Similarly, in the unlikely case of you hearing anything but a perfect tone, you should send a code other than a 9. For the exam, you only need to know that anything other than T9 indicates a problem with the quality of the tone.

Sending realistic RS and RST reports is helpful and you should do that in every QSO. There are two common exceptions to this recommendation: most radio contests,[463] and when working a particularly busy station, such as a rare DX.[464] The IARU guide explains in considerable detail how to handle contests and busy DX stations. Examples:

- On phone (voice): 59 = perfectly readable, very strong signals
- On phone (voice): 59+15 = perfectly readable, very strong signals, 15 dB over 9
- On phone (voice): 44 = readable with practically no difficulty, fair signals
- In Morse: 599 = perfectly readable, very strong signals, perfect tone
- In Morse: 589 = perfectly readable, strong signals, perfect tone
- In Morse: 339 = readable with considerable difficulty, weak signals, perfect tone

461 There are discrepancies between the calibration and readouts of S-meters. A commonly used S-meter should show a reading of 9 when receiving signal of 50 µV (microvolts) on HF, and 5 µV on VHF/UHF, assuming a 50 Ω system. S-meters are further explained in section 13.3.11 S Meter.

462 Unfortunately, there is no generally agreed upon scheme to report other, more common nowadays, signal problems, such as key clicks and splatter.

463 Some contests, such as the popular UKEICC, explicitly ask that no RS or RST should be sent. In many other contests 59 or 599 are always sent, no matter the signal quality! The signal may be very weak and the conditions difficult in a contest, yet the code of 59 or 599 is still sent. While this makes no sense in terms of signal reporting, it is a useful contest practice. It allows both participants, often non-English speaking, amidst heavy noise, to understand the remainder of their contest transmissions (also known as exchanges) just because they both expect and know how 59 or 599 sounds like. This is particularly helpful for those new to contesting, both on phone and CW.

464 A rare DX is a station in a remote part of the world. It can get so busy that there may be dozens of stations trying to call it simultaneously. This is known as a *pile-up*. In the interest of expediting the QSO, only the barest of information is exchanged, almost nothing is repeated, and often the 59 or 599 RST is given regardless of the actual signal conditions, which are usually poor.

29.6 Non-Interference

The radio frequency spectrum is occupied by many other services and their users. National and international regulations require that services do NOT INTERFERE with each other. Such services in Ireland include: Ambulance Service, Fire Service, An Garda Síochána, aviation, maritime, military, navigational aids, radiotelecommunications, satellite communication. Mobile phones and many other essential communication services also rely on their allocated radio frequency bands.

All amateur station frequency bands have maximum power levels that must be adhered to. The Wireless Telegraphy Act makes it illegal to use any frequencies other than those that are authorised by your licence.[465] It also makes it illegal to cause harmful interference to other spectrum users, notably the Radionavigation and Radiocommunications Services.

It is vitally important that under no circumstances you transmit on any frequencies outside of those allocated to the amateur service, or use power levels or operating modes (if listed) other than those detailed in ComReg document *09/45 Amateur Station Licence Guidelines,* including its Annexes, and which are summarised in section 25.3.2.

It is your legal responsibility to ensure that the equipment you use causes no such interference by accident or because of being of poor quality. This is particularly important if you decide to build your own radio equipment, or if you shop for uncertified equipment. Be careful: it is easy to purchase radio equipment that does not meet the legal and regulatory non-interference requirements. Look for the EU CE type approval marks and radio conformity statements in the product manuals and on the packaging, see section 22.12. Bear in mind that it is you, and not the manufacturer or the seller, who has the legal responsibility of regulatory compliance and non-interference with other spectrum users.

You are also required to keep up to date with regards to any changes to the regulations, including changes to permitted frequencies, power levels, and operational modes.

Some of the bands have been allocated to amateur radio on a SECONDARY basis, as explained in 20.5 Primary and Secondary Allocations. You are not allowed to interfere with primary user (non-amateur) communications taking place on those bands. If a secondary allocation band frequency is not clear, do not use it. Stop using it if a non-amateur starts transmitting.

29.6.1 How to Deal with Spectrum Interference?

If you experience or witness a DELIBERATE INTERFERENCE with the amateur radio bands, you should report it. Although only the authorities can take action to resolve it, you can assist by providing the necessary information and evidence through the

465 Wireless Telegraphy (Amateur Station Licence) Regulations 2009, section 7.1(b) at www.irishstatutebook.ie/eli/2009/si/192.

correct channels. Do not confuse deliberate interference with its more everyday EMC forms, see section 18.1 Electromagnetic Compatibility.

Because identifying interference is a complex process, and because its sources may be in other countries, it could be difficult for you to ask all the national authorities to act. For those reasons, there is a dedicated IARU Monitoring System (IARUMS) R1. It will take the steps to remove the interference by following the ITU regulations and by liaising with the national regulatory bodies in the relevant country. IARUMS is interested in reports of all kinds of interference, including wilfully intrusive or illegal transmissions and interference from poorly designed devices.[466] IARUMS R1 has a well-defined process for accepting the evidence, including any recordings.[467] While you could report incidents directly to IARUMS R1, IARUMS recommends that you first report them to the national IARU society, that is to the IRTS in Ireland, who will be in position to work with you to gather the necessary information and to help assess the case. IRTS can also offer general advice regarding interference in unclear cases. To report, please contact the IRTS IARUMS officer, or the IRTS IARU Liaison Officer, see irts.ie/officers.

Nevertheless, should you encounter an individual causing you harmful interference that cannot be resolved once the interfering party has been informed, the correct authority to report this matter to is ComReg. The IRTS are available to assist you should you need advice.

466 These devices can include illegal or poorly made radio transmitters, and other digital devices, such as poor solar PV installations, DSL systems, and a wide range of low power digital devices, many of which are poorly designed and do not meet the current European spurious emission standards.

467 www.iaru-r1.org/about-us/committees-and-working-groups/iarums

30 Further Reading

This study guide would not have been possible without the foundation laid by its previous editions. Both the newly added and previously published content has been sourced or validated using reference literature and the regulations listed below. All of those resources are recommended as further reading whilst and after studying for the HAREC.

30.1 Technical Resources

BIPM, *The International System of Units SI, 9th Edition,* Bureau International des Poids et Mesures, 2019.

C.A. Balanis, *Antenna Theory Analysis and Design, 3rd Edition,* John Wiley & Sons, 2005.

M. Browne, *RSGB Radio Communication Handbook, 14th Edition,* Radio Society of Great Britain, 2020.

J. Devoldere, *ON4UN's Low-Band DXing, 4th Edition,* The American Radio Relay League, 2005.

D.J. Griffiths, *Introduction to Electrodynamics, 4th Edition,* Pearson Education, 2013.

W.H. Hayt, *Engineering Electromagnetics, 8th Edition,* McGraw-Hill, 2012.

M.W. Maxwell, *Reflections III Transmission Lines and Antennas,* CQ Communications, 2010.

S.J. Orfanidis, *Electromagnetic Waves and Antennas,* Rutgers University, 2016.

E.M. Purcell, *Electricity and Magnetism, 3rd Edition,* Cambridge University Press, 2013.

K. Schmidt, *Spectral Analysis of a CW Keying Pulse,* Tempe, 2001.

H.W. Silver, *The ARRL Antenna Book for Radio Communications, 24th Edition,* The American Radio Relay League, 2019.

H.W. Silver, *The ARRL Handbook for Radio Communications, 98th Edition,* The American Radio Relay League, 2020.

K. Siwiak, *Small Gap-Resonated HF Loop Antennas,* QST Sept 2018 pp 30–33, The American Radio Relay League.

S.W. Smith, *The Scientist and Engineer's Guide to Digital Signal Processing, 2nd Edition,* California Technical Publishing, 1999.

J. Woodhouse, *UK Safety Information Regarding ARRL Grounding* and *Bonding for the Radio Amateur,* Radio Society of Great Britain, 2017.

R.L. Yadava, *Antenna and Wave Propagation,* PHI Learning, 2011.

RSGB EMF Team,[468] *EMF Pre-Assessed Configuration – Half-wave dipoles (160m to 40m)* Radio Society of Great Britain, 2020.

RSGB EMF Team, *EMF Pre-Assessed Configuration – Rotatable Beam Antennas for 50 MHz to 1.3 GHz,* Radio Society of Great Britain, 2021.

A.I. Zverev, *Handbook of Filter Synthesis,* John Wiley & Sons, 1967.

30.2 Regulations and Guidelines

- CEPT: The European Conference of Postal and Telecommunications Administrations
- ComReg: Commission for Communications Regulation
- IARU: International Amateur Radio Union
- ICNIRP: International Commission for Non-Ionising Radiation Protection
- IRTS: Irish Radio Transmitters Society
- ITU: International Telecommunication Union

Administrative Council IARU, *Amateur and Amateur-satellite Service Spectrum,* International Amateur Radio Union, 2020.

CEPT ECC, *CEPT Harmonised Amateur Radio Examination Certificate,* Recommendation T/R 61-02, 2020.

CEPT ECC, *CEPT Radio Amateur Licence,* Recommendation T/R 61-01, 2022.

ComReg, *Amateur Station Licence Guidelines,* Document 09/45 R6, 2023.

ComReg, *ITU Emission Designator,* Document 08/34, 2008.

ComReg, *Proposed Strategy for Managing the Radio Spectrum 2022–2024,* Document 21/136A, 2021.

ComReg, *Radio Frequency Plan for Ireland,* Document 20/58 R5, 2023.

IARU Region 1, *IARU Region 1 HF Band Plan,* 2016.

IARU Region 1, *IARU Region 1 VHF Band Plan,* 2020.

IARU Region 1, *General Conference Varna-Albena,* Recommendation VA14_C3_REC_21, 2014.

ICNIRP, *ICNIRP Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz),* Health Physics 118(5): 483–524, 2020.

468 The RSGB EMF Team 2021–23: J. Rogers, I. White, and P. Zollman.

ICNIRP, *ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz),* Health Physics 74(4): 494-522, 1998.

IRTS, *Amateur Radio Emergency Network Handbook,* 2021.

ITU, *International Morse Code,* Recommendation ITU-R M.1677–1, 2009.

ITU, *Minimum qualifications of radio amateurs,* Recommendation ITU-R M.1544–1, 2015.

ITU, *Nomenclature of the frequency and wavelength bands used in telecommunications,* Recommendation ITU-R V.431–8, 2015.

ITU, *Radio Regulations,* Edition of 2020.

ITU, *Spectra and bandwidth of emissions,* Recommendation ITU-R SM.328–11, 2019.

J. Devoldere, *Ethics and Operating Procedures for the Radio Amateur, 3rd Edition,* International Amateur Radio Union, 2010.

Office of the Attorney General, Government of Ireland, *Wireless Telegraphy (Amateur Station Licence) Regulations 2009,* S.I. 192/2009.

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Edition History

Table 30-B: Edition history

Date	Revision	Changes	Authors and Editors
Apr 2006	1.0	CD edition of the IRTS HAREC Amateur Station Licence Course Guide.	Paul Martin EI2CA Sean Nolan EI7CD Séamus McCague EI8BP
2011	1.x	Content expanded. HTML edition.	Joe Ryan EI7GY
2013	2.0	Syllabus updated.	Séamus McCague EI8BP
May 2018	1.11[469]	Converted to PDF.	Frank McKeown EI8HIB
Feb 2020	1.13	Syllabus amended to match updated ComReg guidelines. Updated PDF.	Joe Ryan EI7GY Frank McKeown EI8HIB (PDF)
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INDEX

Entries in the index show the main pages on which each term is discussed. If more than one is shown, **bold** indicates the key page. Consider using the index prior to the exam to find out which concepts to revise.

/M (land mobile), 318, **329**, 337, 359
/MM (maritime mobile), 318, **330**, 337, 359
  permitted bands, 343
/P, 330
/QRP, 359
µF (microfarad), 93
µH (microhenry), 89
A (ampere), 13, **16**
A·h (ampere hour), 26
A1A, **159**, 173, 317
A3E, 145, **156**, 157, 173, 317
abbreviation, operational, **348**, 359
absorption, radio wave, 255
AC (alternating current), **17**, 38
  antenna, 224
  capacitor, 95
  frequency, mains, 44
  inductor, 92
  peak voltage, mains, 44
  peak-to-peak voltage, mains, 44
  period, mains, 44
  rms voltage, mains, 44
  signal, analogue, 142
  sinusoidal signal, 44
  transmission line, 254
acceptor, 103
ADC (analogue to digital converter), 52, 53, **58**, 65, 203
  IC, 126
  SDR, fully digital, 67
  SDR, receiver, fully digital, 200
adverse effect (health), 303
aerial. *See* antenna
AF (audio frequency), 51, **61**, 142
AFSK (audio frequency shift keying). *See* *under* modulation
AGC (automatic gain control), 190, **196**, 205
agency, served, 352
air dielectric, 94
aircraft scatter, 266
alarm system, 283
ALC (automatic level control), 137, 175, **180**, 278
  non-linearity, 289
algorithm, 57
aliasing, 62
allocation status, **316**, 342
alphabet, phonetic, 334
alternating current. *See* AC
AM (amplitude modulation), 141, 142, **145**, 156
  demodulation, 195
  duty cycle, 173
  ITU emission designator, 317
amateur radio emergency data network. *See* AREDN
Amateur Radio Emergency Network. *See* AREN
amateur radio in space. *See* AMSAT
amateur radio space exploration. *See* ARSPEX
amateur service, 315
amateur station licence. *See* licence
amateur teleprinting over radio. *See* AMTOR
Ambulance Service, 316, 352, 370
ammeter, 272
ampere (amp), 13, **16**
amplification factor, 123
amplifier, **134**, 205, 251, 287
  AF, 138
  class, **135**, 138, 139, 174
  CW, class C, 176
  digital, 111
  efficiency, 135
  finals, 172
  FM, class C, 182
  frequency range, 135
  high power linear, 186
  IF, receiver, 194
  IMD, 288
  LC oscillator, 115
  limitations, SDR, 184
  linearity. *See* linearity
  nominal impedance, 173
  output power, 135
  overdriving. *See* overdriving
  receiver, 190
  receiver AF, 196
  RF, 138
  safety, 310

amplifier (continued)
SDR, class A, AB, 185
self-oscillation, 290
SSB, class A, AB, 180
stability, 135
testing, 279
transistor, 123
valve, 124
valve, safety, **298**
amplitude, 38, **39**, 48, 59, 171
in FM, 151
modulation. *See* AM
oscilloscope, 276
shift keying. *See* ASK
AMSAT (amateur radio in space), 268
AMTOR (amateur teleprinting over radio), 317
An Garda Síochána, 316, 352, 370
analogue, 68, **142**
filter, 111
sampling, 58, **61**
SDR, 185
vs. DSP, 51
analogue to digital converter. *See* ADC
anode, 125
antenna, 187, **224**
analyser, 280
beam, **228**, 242
beam, safety, 309
capacitive, 234
danger, 294
directional, 242
dish, **249**, 304
feed point. *See* feed point
field, **225**
G5RV, 235
horn, 250
inductive, 234
isotropic, **228**, 246, 247, 250
magnetic loop, 227, 246, 284, 304
make resonant, 101
mechanical, safety, 299
mesh, 228
modelling, safety, 308
monopole, 238
multiband, **235**, 238
non-resonant, 101, 102, **234**
omnidirectional, 240
parabolic, **249**, 304
quarter-wave. *See* quarter-wave ground plane
tubing material, 228
vertical, 234, 238
Yagi-Uda. *See* Yagi-Uda
antenna tuning (matching) unit. *See* ATU
antialiasing filter, **62**, 67
aperiodic signal, 48
aperture, effective, **249**, 250
APRS (automatic packet reporting system)
emergency use, 351
AREDN (amateur radio emergency data network), 351
AREN (Amateur Radio Emergency Network), 316, 344, 350
ARSPEX (amateur radio space exploration), 268
ASK (amplitude shift keying), 142, 143, **160**, 175
clicks and splatter, 288
atmosphere, 259
atom, 12
attenuation, 106, 206
free space, 262
attenuator, **190**, 203
ATU (antenna tuning unit), 100, 187, **220**, 221, 223, 280
audio frequency. *See* AF
audio frequency shift keying (AFSK). *See under* modulation
audio subcarrier. *See* subcarrier
aurora, **257**, 267
automatic gain control*See* AGC
automatic level control. *See* ALC
automatic packet reporting system. *See* APRS
average power. *See under* power
average value, 42
aviation, 370
azimuth plot, **234**, 241, 245
B (half-power bandwidth), 107
back electromotive force (emf), **89**, 92
balanced, 221
antenna, ATU, 221
modulator, **178**, 278
parallel line, 209
balun, **221**, 285
1:1, 232, 285
choke, 227
current, 222
Maxwell, 223
transformer, 221
ugly, **223**, 285
unun, 223
voltage, 222, **223**
band name, ITU, 342
band opening, 270
band plan, 327, 338, **339**, 357
80 m, simplified, 341
80 m, IARU R1, 339
contest, permitted, 343

band plan (*continued*)
emergency centre of activity, 343, 344
frequency, 342
frequency segment, 339
maritime mobile, permitted band, 343
max bandwidth, 340
preferred mode and use, 340
band-pass filter, **104**, 106, 286
frequency response, 108
IF, 192
schematic, 110
SDR, 65, **112**, 185, 200
selectivity, and, 202
SSB, 179
band-stop filter, **104**, 106
schematic, 110
trap, 238
bandwidth, 60, **107**, 112, 140
−3 dB, 107
AM, 148
CW, 162
excessive, **162**, 166, 175
filter, SSB, 179
FM, 155
folded dipole, 237
FT8, 167
half-power, **107**, 112, 116
IF filter, 193
RTTY, 164
SSB, 157
base, transistor terminal, 122
baseband, **67**, 200
bathroom humour (content of transmissions), 361
battery, 17
safety, 299
baud rate, **144**, 164, 167
beacon, 331, 344
beat frequency oscillator (BFO). *See under* oscillator
best regards (73), 358
BFO. *See under* oscillator
bias, **121**, 122, 136
bipolar junction transistor (BJT). *See under* transistor
bit, **60**, 143
bit rate, bit per second (bit/s), 144
BJT (bipolar junction transistor). *See under* transistor
blackout, 258
blocking, 205
body, human, 293
bonding (earth), 296
braid (coax), 212
branch (circuit), 21
breakthrough, 283
broadband receiver, 65
broadcasting, 361
buffer/driver, 176
business (content of transmissions), 361
C (capacitance), 93
cable. *See* transmission line
call sign, 327
composition, 336
Ireland EI, EJ, 337
order of in a QSO, 360
prefix, list, 323
prefix, when travelling, 322
special event, 329
usage, **337**, 359
capacitance, **93**, 96, 102
capacitive circuit, 98
capacitive impedance, 101
capacitive reactance, **96**, 98
capacitor, **93**, 104, 114, 194, 238
parallel connected, 95
plate area, 93
plate distance, 93
series connected, 95
smoothing, 131
tolerance, 93
variable, **93**, 100, 220
working voltage, 93
capture area, **249**, 250
capture pattern, 228
cardiopulmonary resuscitation. *See* CPR
carrier
frequency, 45, **147**, 153
insertion oscillator (CIO). *See under* oscillator
suppressed, **157**, 178
wave, 45, 48, 114, **141**
wave oscillator. *See under* oscillator
Carson's rule, 155
cathode, 125
CB (citizens band), 338, 358
CE type approval, 283, **332**, 370
centi, 15
centre conductor (coax), 212
centre of activity, emergency, **344**, 351
CEPT (European Conference of Postal and Telecommunications Administrations), **320**, 326
channel, FM, 155
characteristic impedance, 100, 102, **206**, 215, 227
coax, 212
parallel line, 210
charge carrier, 12
chassis, 104

chip, 126
chirp, 176
choke, 88
  common mode, 211, 212, **222**, 227, 285
CIO. *See under* oscillator
circuit, 28
  acceptor, 103
  integrated. *See* IC (integrated circuit)
  LC. *See* LC circuit
  resonant. *See* LC circuit
  tuned. *See* LC circuit
citizens band. *See* CB
Civil Defence, 316, 352
class, amplifier. *See under* amplifier
clicks. *See* key click
clipping, 61, 183, 289
CME (coronal mass ejection), 258
coaxial line, 221, *See under* transmission line
code of conduct, 356
code word, 335
coil, **88**, 127
collector, transistor terminal, 122
Commission for Communications Regulation. *See* ComReg
common base, collector, emitter, 123
common mode current, 211, **214**
  choke, 222
  coax shield, **212**, 221
  EMC, 284
  suppression, 222
communication
  emergency, 315, **352**
  emergency network, 352
  permitted, 315
complex
  impedance, 101
complex number, 101
comprehension (code of conduct), 356
compression, audio, 173, 277
computer, 280, 317
  accessories, interference, 285
  chip, 126
ComReg (Commission for Communications Regulation), 315, 320, **326**, 336, 350, 371
  Amateur Station Licence Guidelines 09/45, 290, 292, **327**, 338, 357, 370
  Radio Frequency Plan for Ireland, 338
conduct, code of, 356
conductivity, 16
conductor, **12**, 16
  metals, 16
  plug, earth, live, neutral, 297
conflict, avoidance, 357
connector, coax, **213**, 284
contact. *See* QSO
contest, permitted band, 343
contesting, 358
continuous wave (CW). *See* CW
control grid, 125
conventional current, 16
conversational mode, **164**, 169
coordinated universal time. *See* UTC
copper, **12**, 16
core, 89
  brass, 89
  dust iron, 223
  ferrite, **89**, 222, 223
coronal mass ejection (CME), 258
corruption, data, 288
counter-electromotive force (emf), 89
counterpoise, **239**, 241
CPR (cardiopulmonary resuscitation), 293
CQ (general call), 362
  DX, long distance, 364
  format, 363
  specific geographic area, 364
critical frequency, 269
cross-modulation, 205
crystal, **113**, 114, 179, 181, 192
current
  alternating. *See* AC
  antenna wire, on, 229
  balun, 222
  base, 122
  changing, 74
  collector, 123
  common mode. *See* common mode current
  conventional direction, 16
  dB ratio, 117
  direct. *See* DC
  gain, 134
  high, safety, 299
  induced, safety, 302
  leakage, **94**, 121
  lethal, **293**, 295
  measurement, 273
  Ohm's law, 22
  parallel connected circuit, 21
  series connected circuit, 20
  standing wave, 218
  transformer, 128
CW (continuous wave), 141–44, **159**, 358
  average power, 171
  bandwidth, 162
  beat frequency oscillator (BFO), 115
  blocking, 205
  dah (dash), 143
  decoder, 182

CW (*continued*)
- distress signal, SOS, 350
- dit (dot), 143
- DSP demodulation, **52**, 200
- duty cycle, 173
- ITU emission designator, 317
- key click filter, 162
- key clicks, 288
- keying waveform, 49, **160**
- Morse key, **160**
- Morse proficiency test, 327
- pause, 143
- Q-code, 346
- receiver, 198
- rise and fall time, 162
- sidebands, 163
- transmitter, 114, **175**

cycle, propagation. *See under* Sun
DAC (digital to analogue converter), 52, **64**, 65
- IC, 126
- limitations, 111

dah (dash), 143
data
- analogue, 142
- baud rate, 144
- bit, 143
- bit rate, 144
- corruption, 288
- digital, 114, **143**, 164, 166
- ITU emission designator, **317**
- keying, shift, 143
- speed, 144
- symbol, 143
- symbol rate, 144

dB (decibel), 61, **116**, 134, 207, 246, 248, 251
dBd (dipole), 247
dBi (isotropic), 247
dBm (decibel-milliwatt), 118
dBW (decibel-watt), **118**, 172
DC (direct current), **17**, 38, 94
DDS (direct digital synthesis), 52, **63**, 65, 67
- oscillator, 191
- receiver, 200
- transmitter, fully digital, 184
- transmitter, hybrid SDR, 185

dead zone, 264
deci, 15
decibel (dB). *See* dB
decibel-watt (dBW). *See* dBW
decoding, 170
deliberate interference, 358, **370**
demodulation, 170, **194**, 200
- DSP, 51, **67**, 68
- filter use, 107

demodulator, **194**, 195
- FM, 195

derogatory remark (content of transmissions), 361
desensitisation, 205
detector, 194
- product, 195

dielectric, **94**, 206
- coaxial cable, 212
- constant, 93

digital, 48, **182**
- analogue converter. *See* DAC
- CW, 159
- filter, 111
- FT8, 166
- interface, 183
- mobile radio. *See* DMR
- mode, duty cycle, 173
- mode, receiver, 196
- RTTY, 164
- signal processing. *See* DSP

digitisation, proper, 52, **61**
dimension symbol, 13
diode, 16, **120**, 122, 124, 276
- light emitting (LED), **121**, 130, 282
- photo, 121
- rectifying, **120**, 130
- rectifying, as detector, 194
- Zener, **121**, 133

dipole. *See under* half-wave antenna
direct current. *See* DC (direct current)
direct digital synthesis. *See* DDS
direct sampling, 67, 199
directivity, 228, 234, **246**, 250, 261
director, Yagi-Uda, 242
disaster, 316
discriminator, 195
dish, **249**, 304
distortion, 62, **287**
- digital, overdriving, 183
- from non-linearity, 137, 174
- harmonic, 137, 180, **287**
- intermodulation (IMD), 137, 180, 205, 278, **288**
- prevention, 106
- spectrum analyser, 278

distress signal, 350
dit (dot), 143
DMR (digital mobile radio), 169
double conversion superheterodyne, 189
double sideband amplitude modulation with full carrier. *See* DSB
driven element, 242
DSB (double sideband amplitude modulation with full carrier), 147

DSP (digital signal processing), **51**, 67, 68, 177, 201
  digital filter, 111
  digital modes, 182
  fast Fourier transform (FFT), 56
  integrated circuit (IC), 126
  SDR, 65
  SDR receiver, 200
  SDR transmitter, 184, 185
  transmitter, modulation, 170
ducting, tropospheric, 267
dummy load, 187, **281**
duty cycle
  modulation, 172
  operational, 172
DX (long distance), 260
dynamic range
  digital, **61**, 66, 68, 116, 200, 201
  receiver, 203
dynamo, 73
E (electromotive force), 17
E (voltage), 19
earth
  bonding, 296
  conductor, plug, 297
  protective, 286, **296**
  RF. *See under* RF
  terminal (point), 296
  TN-C-S, 296
earth leakage circuit breaker. *See* ELCB
Earth-Moon-Earth. *See* EME
ECC (Electronic Communications Committee), 320
Echo Ireland, 3
echo, signal, 265
effective
  aperture, 249, 250
  isotropic radiated power (EIRP). *See under* power
  power, use of dB (decibel), 119
  radiated power (ERP). *See under* power
  voltage, 42
efficiency, **174**, 217
  amplifier, 135
  antenna, 246
EFHW (end-fed half-wave). *See under* half-wave antenna
EI News, 3
EIRP (effective isotropic radiated power). *See under* power
ELCB (earth leakage circuit breaker), **295**
electric
  charge, **12**, 224
  current, **12**, 16
  energy, stored, 94
  field, 71, **85**, 236, 279
  field strength, **85**
  field, antenna, 224
  field, capacitor, 93
  field, polarisation, 229
  motor, 74
  potential, 19
  power, 23
  shock, 293
  strength, 306
electrical length, **208**, 229
electromagnetic
  compatibility. *See* EMC
  field. *See* EMF
  spectrum, 83
  wave, **71**, 74, 81, 83, 224, 254
electromotive force. *See* emf
electron, **12**, 72, 94
Electronic Communications Committee. *See* ECC
electronic valve. *See* valve
electrostatic field, 73
electrostimulation, 304
element, driven and parasitic, 242
elevation plot, **233**, 240, 245
eLicensing, 328
EMC (electromagnetic compatibility), 130, **282**, 332, 371
EME (earth-moon-earth), 268
emergency
  centre of activity, 343, **344**, 351
  communication, 350, **352**
  measures, 354
  network, 352
  responsibility, 353
EMF (electromagnetic field), **71**, 224, 246, 279, 283
  European Commission Final Opinion, 305
  pacemaker, 305
  safety, 302
  strength, 302
emf (electromotive force), 12, **17**, 19, 127
emission, 172, 301
  aggregate, 292
  conducted, 283
  designator, ITU, 142, 156, 157, 158, 160, 164, 166, 168, **316**
  non-ionising radiation. *See under* radiation
  power, 305
  radiated, 282
  spurious, 174, 278, **290**, 332
  spurious, excessive, 283, **287**, 290
emitter, transistor terminal, 122

encoding, 315
energy, 23, **26**
engineering practice, safety, 292
envelope, RF, 276, **277**
equivalent
  capacitance, 95
  inductance, **90**, 95
  radiated power. *See under* power
  resistance, **30**, 95
ERP (effective radiated power). *See under* power
error correction, 166
escape wave, **264**, 269
etiquette, 358
European Committee for Electrotechnical Standards, 292
European Conference of Postal and Telecommunications Administrations. *See* CEPT
event safety, 302
exposure, 301
  calculator, 306
  limit, 301
$\mathcal{E}$ (electromotive force, letter epsilon), 17
F (farad), 93
f (frequency), 40, 91
F1B, 317
F1D, 317
F2B, 317
F2D, 317
F3E, **151**, 158, 173, 180, 317
fading (QSB), 151, 155, **269**
fall time, 162
far field. *See under* field
fast Fourier transform. *See* FFT
feed point, 221, 222, **227**
feed point impedance, 220, **227**, 229
  dipole, folded, 237
  EFHW, 236
  non-resonant antenna, 234
  quarter wave ground plane, 241
  Yagi-Uda, 243
feedback loop, 115
feeder. *See* transmission line
feedline. *See* transmission line
feedline radiation, 207, **208**, 211, 221
ferrite, 222
  ring (bead), 285
FET (field effect transistor). *See under* transistor
FFT (fast Fourier transform), **57**, 111
fibrillation, ventricular, 293
field, 72
  effect transistor (FET). *See under* transistor
  electric, **85**, 236, 279, 302
  electric, antenna, 224
  electric, capacitor, 93
  electric, polarisation, 229
  electric, strength, 306
  electrostatic, 73
  far radiating, 74, 80, **226**, 303, 306, 307
  far radiating, attenuation, 262
  far radiating, ERP, 251
  far radiating, meter, 279
  intermediate, 225
  lines of force, 74
  magnetic, **85**, 127, 224, 279, 302
  magnetic, inductor, 88
  magnetostatic, 73
  near radiating, **225**
  near reactive, **225**, 303, 306, 308
  near reactive, EFHW, 236
  near reactive, EMC, 284
  near reactive, meter, 279
  static, 73
  strength, **85**, 251, 302, 308
  strength meter, 279
  vector plot, 72
filament, 125
filter, 51, **106**
  analogue vs. digital, 111
  antialiasing, **62**, 67
  band-pass, **104**, 106, 286
  band-pass, frequency response, 108
  band-pass, IF, 192
  band-pass, schematic, 110
  band-pass, SDR, 65, **112**, 185
  band-pass, selectivity, 202
  band-pass, SSB, 179
  band-stop, **104**, 106, 238
  band-stop, schematic, 110
  cascaded, 110
  designs, 109
  digital, 111
  high-pass, 108
  high-pass, schematic, 110
  IF, receiver, 192
  key click, 162, 166, 168
  limitations, 290
  limitations, SDR, 184, **192**
  low-pass, **108**, 286
  low-pass, in HF station, 186
  low-pass, key click, **162**, 175
  low-pass, reconstruction, 64
  low-pass, schematic, 110
  notch, **105**, 108
  reconstruction, **64**, 67
  roofing, 192
  SDR, 200

filter (*continued*)
shape factor, 108
SSB, 178
stopband, 108
T and Pi, 109
transition band, 108
finals, 138, **172**
finite impulse response. *See* FIR
FIR (finite impulse response), 57, **111**
Fire Service, 316, 352, 370
FM (frequency modulation), 141, 142, **151**, 158
duty cycle, 173
ITU emission designator, 317
power, 171
receiver, 198
transmitter, 180
folded dipole. *See under* half-wave antenna
force field, 72
forward power, 217
forward voltage, 121
Fourier transform, 56
Franke & Taylor 8. *See* FT8
free space, **246**, 307
attenuation, 262
ERP, **250**, 252
isotropic antenna, 228
propagation, 254
frequency, **40**, 48, **82**
allocation, status, 316
band edges, 342
beacon, 344
carrier, 153
carrier, unsuppressed, 147
checking if in use, QRL?, 362
converter, 68, 69, **182**, 185
converter, IMD, 290
counter, **279**, 332
critical, 269
display, **279**, 332
domain, **53**, 151, 278
domain, filter, 111
domain, modulated signal, 147
fundamental, 45
harmonic, 287
identification, **318**, 337, 360
image rejection, 204
LUF, 271
microwave, 83
mixer, 179, **191**, 195, 203
mixer, IMD, 290
modulating, max, 153
modulation. *See* FM
MUF, 269
multiplier, **181**, 185
multiplier, IMD, 290
not permitted, /MM, 330
range, amplifier, 135
reactance, 91, 96
resonant, **99**, 107, 112, 113
response diagram, 108
shift keying. *See* FSK
spot, 60 m, band plan, 342
stability, receiver, 204
stability, transmitter, 174
transmission line loss, 207
vertical incidence, 269
front-to-back, ratio, 246, **248**
FSK (frequency shift keying), 141, 142, **143**
clicks and splatter, 288
DSP demodulation, 200
duty cycle, 172
FT8, 166
power, 171
RTTY, 164
subcarrier, 196
transceiver, 182
FT8 (Franke & Taylor 8), 141, 142, **166**
baud rate, 144
ITU emission designator, 317
SSB, 177
subcarrier, **183**, 196
fully digital, SDR, **67**
fundamental frequency, 45
fuse, rating, 297
G1B, 168, 317
G5RV, 235
gain
AF, 190, **196**
AGC, 196
antenna, 228, **246**, 250, 251, 305
receiver, 189
RF, **190**
gamma match, 243
gateway, 331
emergency use, 351
general call. *See* CQ
generation, **52**, 65, 111, 170
geomagnetic storm, **258**, 264
giga, 15
grey line, **256**, 261
grid, 125
ground, 104
ground plane, 239
ground wave, 260, **262**, 263, 265
H (henry), 89
half-power bandwidth, **107**, 112, 116
half-wave antenna, **229**
current, 229
dipole, 221, **231**, 246, 250, 284, 304

half-wave antenna (*continued*)
dipole, directivity, 234
dipole, efficiency, 246
dipole, fields, 226
dipole, folded, 237
dipole, gain, 247
dipole, non-resonant, 235
dipole, radiation pattern, 232
dipole, safety, 309
dipole, vertical, 234
end-fed (EFHW), 223, **236**, 284
feed point impedance, 229
length, 230
trap dipole, 238
voltage, 229
half-wave dipole. *See under* half-wave antenna
ham, 358
HAREC (harmonised amateur radio examination certificate), 3, **320**, 327
harmful interference. *See* interference
harmonic, **45**, 276
distortion. *See under* distortion
first, 45
mixer, 179, **191**
multiplier, 182
overtone, crystal, 113
second, 45
unwanted, 49, 106, 287
harmonic distortion. *See* distortion:harmonic
harmonised amateur radio examination certificate. *See* HAREC
Health Services Executive, 316, 352
hearing frequency range, 50
heater element, 125
hertz (Hz), 40
HF (high frequency), **82**, 141
DX, 240
propagation, 256, 257, 260, **265**
propagation, F layers, 260
S9, RS meaning, 197
sampling, **62**, 67
HF station, **186**, 286
Hi-Fi, 138
high frequency. *See* HF
high Q, 112
high-pass filter, 108
schematic, 110
high-power, digital limitations, 111
hop, **260**, 270
horizon, radio, 261
horizontal plane plot, **234**, 241, 245
horizontal polarisation, 86
horn, 250
hybrid, SDR, **68**
Hz (hertz), 13, **40**
I (current), 13, **16**
IARU (International Amateur Radio Union), 3, **314**, 320, 371
band plan, 338, **339**
Emergency Operating Procedures, Region 1, 351
Ethics and Operating Procedures for the Radio Amateur, **356**, 360
Monitoring Service. *See* IARUMS
R1, Region 1, 314
S meter standard, 198
IARUMS (IARU Monitoring Service), 371
IC (integrated circuit), 67, 111, **126**
ICAO (International Civil Aviation Organization)
phonetic alphabet, 334
ICNIRP (International Commission For Non-Ionising Radiation Protection), 292, **300**, 307, 332
identification, frequency, **318**, 337, 360
IF (intermediate frequency), **178**, 190, 191
DSP, 51
filter, 192
SDR, 68
SDR receiver, 200, 201
SDR transmitter, 184
superheterodyne, 189
IIR (infinite impulse response), 57, **111**
image frequency rejection, 204
imaginary part (complex number), 101
IMD (intermodulation distortion). *See under* distortion
immunity, 283
impedance, 100
ammeter, low, 273
capacitive, 101
characteristic, 100, 102, **206**, 215, 227
characteristic, coax, 212
characteristic, parallel line, 210
complex number, 101
dummy load, 281
feed point, 220, **227**, 229
feed point, EFHW, 236
feed point, folded dipole, 237
feed point, non-resonant, 234
feed point, quarter wave ground plane, 241
feed point, Yagi-Uda, 243
gamma match, 243
inductive, 101
load, 173
impedance (*continued*)
magnitude, 102

impedance (*continued*)
match, 100, 173, 187, **215**, 221, 241
matched case, 216
matching, 128
matching, ATU, 220
matching, valve, 125
measurement, 280
mismatch, 217
nominal output, 174
optimum undistorted, 173
output, **173**, 215
purely resistive, **100**, 206, 230
reactive, 100
transformer, **128**, 223, 237
unmatched case, 217, 218
voltmeter, high, 273
indicator, regional, 323
inductance, **89**, 102
equivalent, 90
induction, **73**
inductive
circuit, 98
impedance, 101
reactance, **91**, 96, 98
inductor, **88**, 95, 104, 114, 127, 223, 238
tolerance, 89
variable, **89**, 100, 220
infinite impulse response. *See* IIR
information type, 142
infrared, 70
instantaneous value, 42
insulator, 16
integrated circuit. *See* IC
intercommunication, 315
interference, 322
deliberate, 358, **370**
EMC, 236, **282**
harmful, 137, 175, **288**, 316, 331, 370
with other services, 370
intermediate frequency. *See* IF
intermodulation distortion (IMD). *See under* distortion
internal resistance (battery), 18
International Amateur Radio Union. *See* IARU
International Civil Aviation Organization. *See* ICAO
International Commission For Non-Ionising Radiation Protection. *See* ICNIRP
international radiotelephony spelling alphabet. *See* phonetic alphabet
International Telecommunication Union. *See* ITU
international waters, 318
interval, identification, 318
inverse (square) law, 85, **262**
ionisation, **255**, 257
ionising radiation, 83
ionosphere, 229, 240, 259
D layer, 260
E layer, **260**, 267
F, F1, F2 layers, 260
layer, **259**, 263
Irish Radio Transmitters Society. *See* IRTS
Irish Red Cross, 316, 352
irregular signal, 48
IRTS (Irish Radio Transmitters Society), **3**, 315, 316, 327, 371
island, offshore, 337
isotropic
antenna, **228**, 246, 250
antenna, directivity and gain, 247
radiator, 228
ITU (International Telecommunication Union), **314**, 320, 326, 336, 350, 371
band names, 82
emission designator, 142, 156, 157, 158, 160, 164, 166, 168, **316**
phonetic alphabet and figure code, 334
radio regulations, **314**, 361
region, 314
j (imaginary unit), 101
J2B, 166, 168, 177, 317
J2D, 166, 177, 317
J3E, 142, **157**, 173, 177, 317
jacket (coax), 212, 294
JS8CALL, emergency use, 351
junction (circuit), 21
key click, 62, 162, 174, 175, 278, **288**
filter, 162
keying, **143**, 183
waveform, **160**, 288
kilo, 15
Kirchhoff's laws, 20
kWh (kilowatt hour), 26
L (inductance), 89
ladder line, 209
lag
current, 92
voltage, 97
lake, operating on, 330
land mobile. *See* /M
language, amateur radio, 358
latency, 201
layer, atmospheric, 255
layer, ionospheric. *See under* ionosphere
LC circuit, 99, **102**, 112, 115
parallel, 103
series, 103, 106
series, series vs. parallel connected, 106

LC circuit (*continued*)
  variable, 191
lead
  current, 97
  voltage, 92
leakage current, **94**, 121
LED (light emitting diode). *See* diode:light emitting (LED)
legislation, 327
length, electrical, 208
LF (low frequency), **82**, 260, 262
  propagation, 262, **263**
licence, CEPT
  address, 326
  amendements, 328
  call sign. *See* call sign
  cancellation, 328
  class 1, 320, 322, 328
  class 2, 320, 328
  club, 329
  duration, 328
  eLicensing, 328
  exempt frequencies, 338
  experimenting, 331
  station use by others, 326
licen*See*, 326
light, 70, 83
light emitting diode. *See under* diode
lightning
  arrestor, 300
  risk, 300
limiter, 196
line loss. *See under* transmission line
line radiation, **208**
linear IC, 126
linearity, **134**, 174, 287, 290
  digital modes, 180
  IMD, 288
  receiver, 205
  spectrum analyser, 278
line-of-sight, **261**, 263, 265, 266
lines of force, 86
listening, importance of, **359**, 362
live, conductor, 297
L-match ATU, 220
LO. *See under* oscillator
load, **18**
  dummy, 187, **281**
  parallel connected, 104, **106**
  series connected, 103, 104, **106**
lobe, 245
Local Authorities, 352
local oscillator (LO). *See under* oscillator
logbook, 330, **331**
long distance (DX), 260
long path, 265
loss, line. *See under* transmission line
low frequency. *See* LF
lower sideband (LSB). *See* SSB
lowest usable frequency. *See* LUF
low-pass filter, **108**, 286
  HF station, in, 186
  key click, **162**, 175
  reconstruction, 64
  schematic, 110
LSB (lower sideband). *See* SSB
LUF (lowest usable frequency), 271
m (metre), 41
magnetic
  field, 71, **85**, 127, 224, 279
  field strength, 85
  field, far radiating, 80
  field, inductor, 88
  field, static, 73
  loop. *See* antenna:magnetic loop
magnetostatic field, 73
magnitude of impedance, 102
mains
  plug, wiring, 297
  supply, safety, 295
maritime mobile. *See* /MM
mark, symbol, 143
mast, guy rope, 299
master oscillator. *See under* oscillator
maximum
  power rating, 28
  usable frequency. *See* MUF
MAYDAY, 350
MCB (miniature circuit breaker), 295
measures, emergency, 354
medium frequency. *See* MF
mega, 15
metal oxide dielectric, 94
meter, 293
  ammeter, 272
  cross-needle SWR, 274
  field strength, 279
  multirange, 272
  ohmmeter, 272
  reflectometer, 274
  SWR bridge, 274
  voltmeter, 272
metric prefix, 14
  converting, 15
MF (medium frequency), **82**, 260
  propagation, 256, 262, **263**
mH (millihenry), 89
mica dielectric, 94
micro, 15
microphone, **178**, 296

microwave, **83**, 249, 250, 304
milli, 15
miniature circuit breaker. *See* MCB
minimum sampling rate, **61**, 62, 63
mixer, 69, 179, 185, 189, **191**
mixing signals, 114
mobile
  land. *See* /M
  maritime. *See* /MM
  phone, 370
mode
  conversational, **164**, 169
  digital, 173, **182**, 196, 200
  operating vs. modulation, 141
  time-synced, 166
modem
  hardware, 183
  software, **182**, 196
  software filter, 193
modulated
  signal, 46, 48, 140
modulating
  frequency, max, 153
  signal, **140**, 142, 164
  signal, CW, 160
modulation, 45, 48, 114, **140**, 170
  amplitude. *See* AM
  amplitude shift keying. *See* ASK
  audio frequency shift keying (AFSK), 168
  bandwidth. *See* bandwidth
  depth. *See* modulation:index
  digital signal, 50
  double sideband (DSB), 147
  DSP, 51, **67**, 68
  duty cycle, 172
  filter use, 107
  frequency. *See* FM
  frequency shift keying. *See* FSK
  full, 149, 277
  index, AM, 149
  index, FM, 153
  level. *See* modulation:index
  modern transceiver, 66
  noise. *See* noise
  on-off keying (OOK), **159**, 175
  overmodulation, 149
  phase (PM), 317
  scheme. *See* modulation:type
  SDR, transmitter, fully digital, 184
  SSB. *See* SSB
  subcarrier, SSB, **183**
  type, **141**, 142
modulator
  balanced, **178**, 278
  FM, 181
  IMD, 290
monopole, 238
Moon, 262, 268
Morse Code. *See* CW
Morse key, **160**, 176, 294, 296
Mountain Rescue, 316
MUF (maximum usable frequency), 269
  plot, 270
multi-hop, propagation, 261
multimeter, 272
  safety, 299
multipath, propagation, 269
music, 138, 361
nano, 15
narrow band frequency modulation, 155
National Short Wave Listeners Club, 5
NATO (North Atlantic Treaty Organization)
  phonetic alphabet, 334
navigational aids, 370
NBFM (narrow band frequency modulation), 155
NCO (numerically controlled oscillator). *See under* oscillator
near field. *See under* field
nervous system, 304
net power, 217
net, emergency, 352
neutral, conductor, 297
nF (nanofarad), 93
noise, 63, 106, 202, 258, 267
  AM, 151
  atmospheric (QRN), 271
  factor, 204
  figure, 204
  floor, 205
  FM, 155
  man-made (QRM), 271
  phase, 112, 290
  removal, 58
nominal output impedance, 174
non-ionising radiation. *See under* radiation
non-linearity. *See* linearity
non-pecuniary interest, 315
non-periodic signal, **48**, 50
non-resonant antenna, 101
non-sinusoidal signal, **48**, 53
North Atlantic Treaty Organization. *See* NATO
northern lights. *See* aurora
notch filter, **105**, 108
NPN. *See* transistor:bipolar junction (BJT)
NSWLC (National Short Wave Listeners Club), 5
n-type, **16**, 120, 122
nuclear radiation, 83

null, 245
numerically controlled oscillator (NCO). *See under* oscillator
Nyquist frequency, 61
Nyquist rate, 61
offshore island, 337
ohm (Ω), **21**, 28, 91, 96, 98, 100
Ohm's law, **22**, 91, 102
ohmmeter, 272
omnidirectional, 240
on-off keying (OOK). *See under* modulation
open wire, 209
operational abbreviation, **348**, 359
operational duty cycle, 172
orbiting satellite carrying amateur radio (OSCAR), 268
oscillation, **71**, 75, 224
  parasitic, 278, **290**
  self, 290
oscillator, **113**, 115, 130, 205
  beat frequency (BFO), **115**, 195
  carrier insertion (CIO), **115**, 195
  carrier wave, **114**, 176
  direct digital synthesis (DDS), 191
  local (LO), **114**, 190
  master, **114**, 176
  numerically controlled (NCO), 52, **64**, 65, 126
  resonant circuit, 115
  variable frequency (VFO), **115**, 141, 179, 278
oscilloscope, 53, **276**
outer conductor (coax), 212
output impedance, **173**, 215
output network, 173
output power. *See under* power
over. *See under* QSO
overdriving, **137**, 186, **290**
  cross-modulation, 205
  digital, audio level, 183
  distortion, interference, 288
  excessive bandwidth, 167
  non-linearity, **174**, 180, 287
overload, **61**, 197, 203
overmodulation, **149**, 277, 290
oversampling, 63
overtone, 113
P (power), 23
pacemaker, 305
packet radio, 317
paper dielectric, 94
parallel
  connected circuit, 21
  LC circuit. *See under* LC circuit
  line, **209**, 218, 219, 221
  tuned circuit. *See under* LC circuit
parasitic
  element, 242
  oscillation, 278, **290**
particle, high energy, 258
passive infrared sensor (PIR), 283
path, long and short, 265
pause, in CW, 143
PCB (printed circuit board), 28
peak
  deviation, 153
  envelope power (PEP). *See under* power
  inverse voltage (PIV), 121
  voltage, 39
peak-to-peak voltage, 43
PEP (peak envelope power). *See under* power
period, 39, **40**, 48
periodic
  non-sinusoidal signal, 48
  signal, **40**, 49
permitted communication, 315
personal aim, 315
PES (principal emergency service), 352
pF (picofarad), 93
phase, **44**, 92, 167
  difference, 44
  locked loop. *See* PLL
  modulation (PM). *See under* modulation
  noise, 290
  shift keying. *See* PSK
phase shift keying. *See* PSK
phone, **141**, 177
  ITU emission designator, 317
phonetic alphabet, **334**, 358
photodiode. *See under* diode
Pi filter, 109
pico, 15
piezo-electric effect, 113
PIR (passive infrared sensor), 283
PIV (Peak Inverse Voltage), 121
PL-259, 213
plastic dielectric, 94
plate, valve, 125
PLL (phase locked loop), 195
PM (phase modulation). *See under* modulation
PNP. *See under* transistor
polarisation, **86**, 229, 261
politeness (code of conduct), 356
politics (content of transmissions), 361
portable, 330
potentiometer, 29
power, **23**, 70, 107
  absolute, in dBW, 118

power (*continued*)
amplifier. *See* amplifier
average, 171
current, and, 24
density, 85, 302
diode. *See under* diode
effective isotropic radiated (EIRP), 119, 171, 229, **250**, 306, 343
effective radiated (ERP), 119, **250**
emissions, safety, 305
forward, **217**, 274
gain, 134
limit, 327, 329, 330, **342**
loss in transmission line. *See under* transmission line
meter, 274
net, **217**, 274
Ohm's law, and, 24
output, 135, **171**, 251, 283
peak envelope (PEP), **171**, 251, 343
rating, **29**, 121, 207
ratio, 117
reflected, **217**, 274
resistance, and, 24
supply, 17, 120, **129**, 176, 293
supply, linear, 129
supply, safety, 298
supply, switched mode, 129, 130
transfer, 174, 187, **215**, 220
voltage, and, 24
power amplifier, 65
Power Supply Unit (PSU). *See under* power
PRA (principal response agency), 352
primary status, **316**
principal emergency service. *See* PES
principal response agency. *See* PRA
processor, 65
product detector, 195
propagation, 71, **254**
beacon frequency, 344
cycle, daily, 255
cycle, solar, 256
grey line, **256**, 261
ground wave, **262**, 263, 265
hop, multi-hop, 261, 270
line-of-sight, 229, **261**, 263, 265, 266
multipath, 269
path, long and short, 265
satellite, 268
sky wave, 240, **263**, 265
solar. *See under* Sun
space wave, 266
tropospheric wave, 266
velocity, 254
proton, **12**, 94
PSK (phase shift keying), 142, 143, **167**
clicks and splatter, 288
DSP demodulation, 200
transceiver, 182
PSK31, 317
PSU (power supply unit). *See under* power
p-type, **16**, 120, 122
pulse shaping, **162**, 166, 168, 288
pure sine wave, **38**, 45, 114
purely resistive, **100**, 102, 206
Q factor, 112
Q-code, **346–49**, 359
as question or answer, 348
QPSK (4-PSK), 143
QRL?, 362
QSO, 360
call to a specific station, 365
content, 361
CQ (general call). *See* CQ
over, 360
replying, 366
RST signal report, 367
subjects to avoid, 361
transmission, 361
quadrature amplitude modulation. *See* QAM
quality factor. *See* Q factor
quantisation, 57, **59**, 62
error, 63
step, 60
quarter-wave ground plane, 238
feed point impedance, 241
radiation pattern, 240
quartz crystal, **113**, 115
R (resistance), 21
radial, **239**, 241
radiating field, 74
radiation, 70
exposure calculator, 309
ionising, 83
non-ionising, 83
non-ionising, emissions, 292
non-ionising, safety, **300**, 302, 310
nuclear, 83
pattern, 305
safety, 300
spurious. *See under* emission
radiation pattern, **228**
half-wave dipole, 232
quarter wave ground plane, 240
Yagi-Uda, 243
radiator. *See* antenna
radio, 170
blackout, 258
emissions directive. *See* RED
frequency. *See* RF

radio (*continued*)
 horizon, 261
 spectrum, 3, **83**
 wave, **70**, 81
radio spectrum, **83**
radioteletype. *See* RTTY
ragchew, 2, **358**
ratio, decibel, 116
ratio, front-to-back, 246, **248**
RCD (residual current device), **295**, 299
reactance, **98**, 100, 112
 capacitive, 234
 inductive, 234
reactive
 circuit, **100**, 102
readability, RST code, 368
real part (complex number), 101
receiver, 51, 67, 68, 170, **188**
 AM, 195
 broadband, 65
 characteristics, 202
 CW, 195, 198
 FM, 195, 198
 S meter, 197
 SDR, fully digital, 199
 SDR, hybrid, 201
 SSB, 195, 198
 superheterodyne, 68, **188**, 201, 203
 superheterodyne, double conversion, 189
 superheterodyne, triple conversion, 201
reconstruction filter, **64**, 67
rectification. *See* rectifier
rectifier, 130
 bridge, 132
 full-wave, 132
 half-wave, 131
rectifying diode. *See under* diode
RED (radio emissions directive), 279, **332**
reduction of hazardous substances. *See* RoHS
reference clock, 64
reflected power, 217
reflection (propagation), **260**, 263
 auroral, 267
 radio wave, 255
reflectometer, 274
reflector, Yagi-Uda, 242
refraction, 255, **260**, 263, 264
regional indicator, 323
regulations
 CEPT, recommendations, 320
 Irish, 326
 ITU, 314
rejector, circuit, 103
religion (content of transmissions), 361
remarks of personal character, 362
remote station, 331
repeater, **266**, 331
 emergency use, 351
requirements, technical, 331
residual current device. *See* RCD
resistance, 16, **21**, 28, 100, 101, 112
 equivalent, in parallel, 30
 equivalent, in series, 30
 measurement, 273
 Ohm's law, 22
resistor, **28**, 194
 maximum power rating, 28
 mulitple in circuit, 32
 parallel connected, 30
 power total, 34
 series connected, 30
 symbol, 28
 terminals, 28
 tolerance, 28
resolution, **60**, 62, 66, 200, 201, 203
resonance, **98**, 103, 104, 113, 229
 dipole, 235
resonant
 circuit. *See* LC circuit
 frequency, **99**, 107, 112, 113
RF (radio frequency), **82**, 206, 212
 burn, 215, 230, 284, **294**, 304
 DSP, 51
 earth, 215, 221, 236, 284, **287**, 296
 envelope, 276, **277**
 sampling, 62
 SDR, **67**, 68, 184, 200
RG-213, 213
RG-58, 206, **213**
rig, radio, 170
rise time, **162**, 288
river, operating on, 330
rms (root mean square), **42**, 91, 96, 102
RoHS (reduction of hazardous substances), 300
roofing filter, 192
rotator, 242
RST, RS code, 367
RTTY (radio teletype), 141, 142, **164**, 200, 346
 demodulation by DSP, 52
 duty cycle, 172
 ITU emission designator, 317
 shift, 164
 subcarrier, 196
 symbols, 143
 transceiver, 182
S meter, 369

S meter, point, **197**, 246
Safe Electric National Rules for Electrical Installations Completion Certificate, 295
safety, 331
  adverse effect, 303
  electrical, **293**, 295
  exposure limit, 301
  legislation, 292
  mechanical, 292
  nervous system, 304
  people and property, 292
sample, 59
sampling, 57, **58**, 65, 111
  direct, receiver, 199
  rate, 60
  rate, fully digital SDR, 200
  rate, hybrid SDR, 201
  rate, minimum, **61**, 200
SAR (specific absorption rate), 302
satellite, **268**, 315
scattering
  aircraft, 266
  auroral, 267
  meteor, 267
  tropospheric, 266
SDR (software defined radio), 51, **64**, 177, 182
  filters, 111
  frequency stability, 205
  oscillator, 114
  receiver, direct sampling, 199
  receiver, fully digital, 199
  receiver, hybrid, 201
  transmitter, fully digital, 184
  transmitter, hybrid, 182, 185
selectivity, 188, 189, 190, 194, **202**, 204
self-discipline, 357
self-oscillation, 290
self-regulation, 338, **357**
self-training, 315
semiconducting junction, **16**, 120, 122
semiconductor, **16**, 120, 122
sensitivity, 188, 190, **202**, 205
  IMD, 205
series
  connected circuit, 20
  LC circuits. *See under* LC circuit
  tuned circuit. *See under* LC circuit
served agency, 352
shape factor, 108
shield (coax), 212, 294
shielding, 286
shift keying, 143
ship's master, 330
shock, electric, 293
short circuit, 18
  current, 18
short path, 265
shorting stick, 298
short-wave listener, 326
SI (International System of Units), 13
sideband, 140
  AM, 148
  CW, 163
  FM, 151
  SSB, 157
  SSB, removal, 178
signal
  analyser, 53
  baseband, 200
  control, 315
  distress, 350
  generator, 277, **278**
  mixer, 189
  modulated, 140
  modulating, **140**, 142, 164
  modulating, CW, 160
  non-periodic, 48
  non-sinusoidal, 48
  periodic, **40**, 48
  return, 104
  RST report, 367
  strength, 38
  strength, RST code, 369
  to noise ratio. *See* SNR
silicon, 16
sine wave, **38**, 195
single sideband. *See* SSB
sinusoidal signal, **38**, 82, 114, 160
  modulated, 45
  phase, 44
skin effect, 227
skip distance, 264
sky wave, 240, **263**, 265
slow-scan television. *See* SSTV
SNR (signal to noise ratio), **60**, 190
  decibel, 116
  IMD, 205
  noise figure, 204
  receiver, fully digital, 200
  receiver, hybrid, 201
  SDR, fully digital, 67
  SDR, hybrid, 68
  sensitivity, 202
SO-239, 213
social feeling (code of conduct), 356
software, 164
  modem, **182**
software defined radio. *See* SDR

solar panel, 282
soldering, safety, 300
solid state, **17**, 273
  limitations, 217
SOS, 350
southern lights. *See* aurora
space
  free, **246**, 307
  free, ERP, **250**, 252
  free, isotropic antenna, 228
  free, propagation, 254
  symbol, 143
  wave, 266
specific absorption rate. *See* SAR
spectrogram, 52, 200
spectrum, 83, 278
  analyser, 278
  radio, 3
speech, **50**, 62, 173
speed
  CW, 162
  data, 144
  FT8, 167
  light (c), **41**, 70, 254
  RTTY, 164
spelling, alphabet, 334, 358
splatter, 62, 174, 175, 278, **288**
sporadic E, 260, **267**
spot frequency, 342
spurious emission. *See under* emission
square wave, 49
squelch, 198
SSB (single sideband), 51, 141, 142, **157**
  bands, 341
  duty cycle, 173
  ITU emission designator, 317
  LSB, 147, **157**
  LSB/USB use, 341
  power, 171
  receiver, **198**, 205
  RF envelope, 277
  transmitter, 177
  USB, 147, **158**, 166
SSTV (slow-scan television), 169
stability, 135
  receiver, 204
standing wave, **218**, 275
standing wave ratio. *See* SWR
static
  discharger, 300
  electric field, 73
  electricity, 73
  field, 73
  magnetic field, 73
station
  licence. *See* licence
  use by-unlicensed persons, 326
station, HF, **186**, 286
status, allocation, 342
  primary, 316
  secondary, **316**, 370
stopband, 108
storm, geomagnetic, 258, 264
strap, earth, 296
subatomic particles, 12
subcarrier, **166**, 168, 188, 196
  ITU emission designator, 317
  SSB, 177
subjects to avoid, 361
Sun, 255
  cycle, daily, **255**, 269
  cycle, solar, **256**, 269
  day, 255
  flare, 257
  flux, 257
  grey line, **256**, 261
  maximum, **256**, 258
  minimum, 256
  night, 255
  radiation, 255
  sunspot, full rotation, 257
  sunspot, 257
  sunspot number, 257
sunrise, 256
sunset, 256
superhet. *See under* receiver
switch, main (master), **295**, 299
SWR (standing wave ratio), **219**, 274
  bridge (meter), 186, **274**, 332
  measurement, **274**, 280
  standing wave, **218**
  troubleshooting, 281
symbol, **143**, 166
  rate, **144**, 164, 167
  SI, lowercase vs. uppercase, 13
  SI, table, 14
synthesis, 52, 65, 111
System Fusion, 169
T filter, 109
T/R 61-01, **320**, 322, 327
T/R 61-02, **320**, 327
technical investigation, 315
technical requirements, 331
telegraphy, **159**, 164, 168, 293
  ITU emission designator, 317
telemetry, 317
telephony. *See* phone
teleprinter, 164
teletype (TTY), 164
temperature inversion, 267

terminal, **16**, 120, 122, 126, 221
  voltage, 18
territorial waters, 316
test, two-tone, 277
thermionic device. *See* valve
thermosphere, 259
thunderstorm, antenna precaution, 300
time domain, 38, 49, **53**, 151, 276
  filter, 111
  modulated signal, 147
time, rise and fall, 288
time-synced, mode, 166
T-match ATU, 220
tolerance
  capacitor, 93
  code of conduct, 356
  inductor, 89
  resistor, 28
tone
  RST code, 369
  symbol, **143**, 166
toroid, **222**, 285
tower, antenna
  lightning risk, 300
  location, 299
transceiver, **170**, 188, 277
transformer, **127**, 129, 223
  balun, 221
  current, impedance, voltage ratios, 128
  isolation, 128
  power loss, 129
  step-down, 128
  step-up, 128
  turns ratio, 128
  voltage, power supply, 129
transistor, **122**, 124, 172
  bipolar junction (BJT), **122**, 123
  bipolar junction (BJT), currents, 122
  field effect (FET), **123**, 125
  gain, 123
transition band, 108
transmission. *See under* QSO
transmission line, 94, 102, 173, 187, **206**, 254
  balanced, 209
  coaxial, 100, **211**, 221, 284, 294
  coaxial, common mode, 215
  damage, 218
  loss, **206**, 251
  loss, dielectric, **207**, 218
  loss, parallel line, 210
  loss, resistive, **207**, 218
  parallel, **209**, 218, 219, 221, 232, 285
  parallel, common mode, 215
  radiation, 208
  waveguide, 213
transmitter, 51, 67, 69, **170**, 251
  CW, 175
  digital mode, 182
  FM, 180
  SSB, 177, 185
  testing, 279
transverse wave, 80
transverter, 186
trap, 238
trap dipole. *See under* half-wave antenna
triode, 124
troposcatter, 266
troposphere, 259
tropospheric ducting, 267
tropospheric wave, 266
TTY (teletype), 164
tuned circuit. *See* LC circuit
tuning knob, **115**, 190
turns ratio. *See under* transformer
twin feeder, 209
twin lead, 209
two-tone test, 277
UHF (ultra high frequency), 82
  FM bandwidth, 155
  FM modulation index, 153
  line loss, 207
  noise figure, 204
  oscillator, 181
  parabolic antenna, 249
  propagation, 266
  sampling, 68
  waveguide, 214
ultra high frequency. *See* UHF
UN (United Nations), **314**
unbalanced, 211, 212
unit symbol, 13
United Nations (UN), 314
unun, 223
upper sideband (USB). *See* SSB
USB (universal serial bus), 182
USB (upper sideband). *See* SSB
UTC (coordinated universal time), 331
UV (ultraviolet), 255
V (volt), **17**, **19**
V (voltage), 19
vacuum
  free space, 262
  tube. *See* valve
valve, 17, **124**, 172
  safety, 298
variable
  capacitor, **93**, 100
  frequency oscillator (VFO). *See under* oscillator
  inductor, 100

vector network analyser. *See* VNA
vector plot, 72
vehicle, land operation, 329
velocity factor, 208
  coax, 212
  parallel line, 210
vertical incidence frequency, 269
vertical plane plot, **233**, 240, 245
vertical polarisation, 86
very high frequency. *See* VHF
VES (voluntary emergency service), 352
VHF (very high frequency), **82**, 141
  FM bandwidth, 155
  FM modulation index, 153
  line loss, 207
  noise figure, 204
  oscillator, 181
  propagation, 257, 260, **266**
  S9, RS meaning, 197
  sampling, 62
  SDR, 200
vibration, crystal, 113
video, 114, 142
visiting, other countries, 320, **322**
VNA (vector network analyser), 280
voice, 48, **50**, 114, 138
  ITU emission designator, 317
volt, **17**, **19**
voltage, **17**, **19**
  antenna wire, on, 229
  back emf, 90
  balun, 222, **223**
  bias, **121**, 122, 137
  dB ratio, 117
  drop, 121
  forward, 121
  gain, 134
  high, **186**, 237, 293, 298, 299, 310
  measurement, 273
  Ohm's law, 22
  oscilloscope, 276
  parallel connected circuit, 21
  peak, 39
  peak inverse, 121
  peak-to-peak, 43
  rating, tranmission line, 207
  regulator, 133
  rms (root mean square), 42
  series connected circuit, 21
  source, 17
  source, parallel connected, 18
  source, series connected, 18
  stabiliser, 133
  standing wave ratio (VSWR). *See* SWR
  terminal, 18
  transformer, 128, 129
voltmeter, 19, 59, **272**
  safety, 299
voluntary emergency service. *See* VES
VSWR (voltage standing wave ratio). *See* SWR
W (energy), 26
W (watt), **23**, 28, 172
waterfall, 53, 56, **65**, 200, 278
waters
  international, 318, 330
  operating on, 330
  territorial, 316
watt (W), **23**, 28, 172
wave formation, 75
waveform, 137
  keying, **160**
waveguide, **213**, 304
wavelength, **40**, 48
Weak Signal Propagation Reporter. *See* WSPR
Wi-Fi, 169
wind load (antenna), 299
window line, 209
Winlink, emergency use, 351
Wireless Telegraphy (Amateur Station Licence) Regulations 2009, 292, **326**, 370
words per minute. *See* WPM
work (make contact), 358
work (physics), 23
working voltage, 93
WPM (words per minute), 144
WSJT-X, 267, 268
WSPR (weak signal propagation reporter), 118, 183
X (reactance), 98
X_C (capacitive reactance), 96
X_L (inductive reactance), 91
x-ray, 83
Yagi-Uda, 221, **242**, 268, 284, 304
  capture area, 249
  efficiency, 246
  front-to-back, 248
  length, elements, 243
  radiation pattern, 243
Z (impedance), 100
Z_0 (characteristic impedance), **206**
Zener diode. *See under* diode
β (transistor gain, letter beta), 123
λ (wavelength, letter lambda), 41
π (Pi), 91
Ω (ohm), **21**, **91**, 96, 98, 100, 206

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IRTS HAREC Amateur Radio Station Licence Study Guide

The authors of this book are experienced tutors at the National Short Wave Listeners Club (NSWLC), which is affiliated with the Irish Radio Transmitters Society (IRTS). They teach courses for prospective radio amateurs who wish to obtain the Harmonised Amateur Radio Examination Certificate (HAREC) to get their station licence. The team, led by Rafal EI6LA, wrote this book for anyone who wants to take the Irish licensing examinations, including those learning on their own, and those attending courses. This guide intends to be complete and self-contained. Anyone who uses it should be able to pass the exam without a need for an extensive use of other sources.
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The IRTS has compiled an impressive array of information, both practical and technical. Although written with the express purpose of preparing one to successfully pass the Irish HAREC licensing examination, this book does far more. Its goal is clearly not just to achieve passing examination marks, but to do so with a practical understanding of the material that is being tested. Lest a non-technical person be dissuaded by the large amount of technical content, this book leads a person with no technical background through the basics to reach an understanding of the technical material. By learning what this book offers, you can become a member of a worldwide fellowship that I have enjoyed for over 50 years.
Greg Lapin N9GL · ARRL RF Safety Committee Chairman

This book fills a useful niche between the shorter exam study guides and the major amateur radio handbooks. Its primary focus is the Irish HAREC exam, but it also makes good background reading for anyone studying for the UK Advanced or Direct-to-Full exams – and indeed, for anyone who wants to explore beyond the exams.
Ian White GM3SEK · RSGB EMF Team & Technical Author

You have in your hands a book designed to help you discover our hobby, give you the elements necessary to prepare for the exam and guide you to your first contacts. Technical aspects, regulatory framework, best practices… The team of authors covers in this book everything you will need to join us on the air very soon!
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